UNIVERSITY OF TRENTO - Italy

CIMeC Center for Mind/Brain Sciences

Doctoral school in Cognitive and Brain Science

XXXI cycle

Ph.D. Dissertation

ERP correlates of semantic and syntactic processing in cochlear implant users.

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Chapter 1

1 – Deafness, cochlear implants and language

1.1 – Introduction to deafness

Along with blindness, deafness is probably one of the most studied sensory deprivation in the history of cognitive neuroscience. Studies on people who experienced some sort of sensory deprivation allows clinicians and researchers to formulate and test new hypotheses on the development of brain and cognition. Deaf and blind populations represent a crucial sample to study how experience can shape the neural and functional architecture of the brain. In many deaf individuals, brain's development is typical, with auditory cortices and networks ready to receive an external sensory input. Therefore, considering that the normally developed brain is ready to receive acoustic stimulation and that brain cortex is susceptible of the plasticity phenomenon, the absence of the peripheral stimulation can initiate an interesting modification/reallocation of the auditory cortices and networks (see for example: Auer & Bernstein, 2007; Bolognini et al., 2011; Finney, Clementz, Hickok, & Ca, 2003; and see also Voss & Zatorre, 2012 for a comprehensive review). In this thesis, we will be focusing only on sensory deprivation caused by deafness and, from now on, every reference to *sensory deprivation*, *sensory loss* and similar linguistic forms will be exclusively referred to **auditory** deprivation.

1.1.1 – What is deafness and how does it manifest

Deafness is a sensory deficit that causes a reduction of auditory information processing with different degrees of severity. It can be unilateral or bilateral depending on the etiology and the causes of deafness itself. Among others, hearing deprivation, both from birth or originated later in life, entails a reduced ability to perceive dangers in the environment, as well as the reduced or absent ability to orient to distal stimuli conveyed through sounds. Most importantly however, deafness impacts on the ability to communicate through oral language. Particularly in those individuals who are born deaf or became deaf before language acquisition, firm consolidation of language is at risk and greatly challenged. Deafness has an incident rate around 1.2 ‰ of bilateral hearing loss cases among live newborns (Bouillot, Vercherat, & Durand, 2019) with a prevalence in the US of 1.7 ‰ according to a large scale of infant screening ("Annual Data Early Hearing Detection and Intervention (EHDI) Program", 2016). The etiology and the type of deafness can be quite heterogeneous, but it can be divided in three main categories. First, conductive deafness has been linked to an amplification, transformation and transmission of sounds to the cochlea through the external and the middle ear. People suffering from this type of deafness transfer only a limited amount of the mechanical energy of sounds to the inner ear, but retain the ability transduce this energy into neural impulses. Second, deafness of sensorineural origin, which can be ascribed to problems linked with the cochlea (cochlear deafness) or to cochlear-nerve related issues which is described as retro-cochlear deafness. People suffering from this type of deafness lose partially or completely the ability to transduce mechanical energy into neural impulses. Third, central deafness, which is assumed to reflect disfunctions occurring in the primary auditory cortex that is located beyond the processing stages of transmission and transduction of sound energy.

Deafness is also characterized by several levels of severity depending on the overall amount of hearing loss and frequencies degradation that deaf individuals experience. Audiological tests typically probe frequencies established in advance: 500Hz, 1000 Hz, 2000 Hz and 4000 Hz. If the average tonal loss is less or equal to 20 dB, hearing is considered to be normal or sub-normal. Between 21- and 40-dB deafness is considered as *minor,* whereas it is *moderate* if the hearing loss is between 41- and 70-dB (41-55 dB = 1st level; 56-70 dB = 2nd level). According to the internationally recognized classification of deafness (International Bureau for Audiophonology, 1996), up to this level of severity, it is still possible to perceive and correctly process human spoken language. Of course, with higher degrees of hearing loss, more strategies should be adopted in order to facilitate hearing impaired people to better discriminate linguistic information from the environment (e.g. speaking loudly and in front of them). With over 71-dB of hearing loss, deafness is considered to be *severe* (71-80 dB = 1st level; 81-90 dB = 2nd level) and it is defined as *profound* at over 91-dB of hearing loss (91-100 dB = 1st level; 101-110 dB = 2nd level; 111-119 = 3rd level). If at the 3rd stage some very loud noise can still be perceived, when the loss passes the 120-dB value, no auditory stimulus can be perceived at all. At these stages, spoken language processing is completely compromised because of its impossibility to be perceived leading to the diagnosis of *profound* deafness.

Given the variety of deafness' etiology, deafness can occur throughout the lifespan. Furthermore, the progression of the severity of the condition is far from being uniform between individuals because of the aforementioned variety of etiologies. This entails that there are people born deaf and individuals who become deaf later in life (immediately or gradually). As we will see in the next paragraphs, it is crucial to conceptually distinguish individuals who became deaf before or during acquisition of their first language (prelingual deaf) from those who acquired deafness after language acquisition had already occurred (postlingual deaf). Belonging to one or the other group depends on whether deafness occurred before or after the consolidation of a first language (L1). Typically, people who became deaf within the first 18 months of age are considered prelingually deaf; those who become deaf by the 3.0/3.5 years of age are considered peri-lingually deaf; and those who acquired deafness at older ages are included in the postlingual sample. This distinction is crucial for all of the studies that involve language acquisition, development and processing in auditory deprived individuals. Further details will come in the next two paragraphs; however, we anticipate here that we have adopted the conservative approach to treat pre- and peri-lingual deaf participants as a single group of individuals for which deafness could have impacted on L1 acquisition. While conceptually clear, the distinction between pre/peri lingual and post-lingual is difficult to establish clear cut in reality. In the past decades, but still today around the world and in some regions of Italy, early diagnosis is not yet part of the clinical practice often resulting in a delayed deafness recognition. Moreover, acoustic deprivation can sometimes be hard to diagnose, especially in cases of mild or partial deafness. The case of after-birth onset for example, can be very hard to be recognized even for parents due to the nature of newborns and infants lack of communication.

1.1.2 – Early deafness and cognition – language (deaf children of hearing parents)

Children who are born deaf or become deaf at the beginning of their life (i.e., before the age of 3.5 years) are at risk of delays in both language comprehension and language production (Caselli, Maragna, & Volterra, 2006; Rinaldi & Caselli, 2009; Spencer & Marschark, 2006). Psychologists, linguists and cognitive neuroscientists have investigated the impact of early auditory deprivation on language development and processing with two parallel aims. On the one hand, language development in children who are early deaf can shed lights onto the mechanisms and sensitive periods for language development. On the other hand, it is of primarily importance to identify the best possible strategies for promoting language in this auditory deprived population.

The key problem is that more than 95% of deaf infants are born from parents who are unprepared to face communication difficulties in the oral language and, in general, unaware of best strategies for interacting with children who are deaf (Humphries et al., 2018). This translates a not negligible risk of an underexposure to linguistic input, and in turn the risk of incomplete first language acquisition. A large number of studies in English demonstrated a significant delay in language experience in both vocabulary and grammar in deaf children who were exposed exclusively to a verbal L1, with worse performances in the deaf group when compared with matched peers (Mayne, Yoshinaga-Itano, Sedey, & Carey, 1998; Spencer & Marschark, 2006; Yoshinaga-Itano, 2014). Language proficiency of children ranging from 1 to 10 years old without any hearing aid has been investigated aiming to better understand how deafness impacts language acquisition (see Caselli et al., 2006 for a comprehensive review). Unfortunately, even the advent of modern hearing aids or cochlear implants has not eliminated the risk of partial language development (see below).

The impact of language deprivation caused by deafness has been investigated also in Italian where deaf children, half educated with the oral and half with the bimodal approach. Bimodal approach implies that the acquisition of the oral first language is also accompanied by the use of gestures or signs from sign language. Both sign language (i.e. Italian Sign Language) and signed language (i.e. Signed Italian) take advantage of an intact modality (vision) which should allow children to better acquire their L1. In this case, children coming from both approaches showed a significant delay either in grammatical and vocabulary tasks when compared to normal hearing and age-matched controls (Rinaldi & Caselli, 2009). Tested children produced shorter and less complex sentences, containing fewer function words such as pronouns and articles highlighting that even in the very first years of language acquisition, basic structures of syntax can be affected. However, they also showed that this delay does not exist when the exposure to language is comparable between deaf and hearing children leading to the conclusion that the lack of language experience (and not deafness itself) is the key factor for language delay. To corroborate the dissociation between grammar and lexicon, they demonstrated that, although both affected by the delay, deaf children proved to have more issues with grammar rather than with vocabulary. Longitudinal studies already highlighted the difficulties of early-deaf children in both written production and comprehension of free-standing grammatical morphemes in Italian language further suggesting syntactic weakness in this population (Volterra, Capirci, & Caselli, 2010). As we will better discuss later, this dissociation is primarily relevant for the aim of our study.

Hearing impairments that occur during the first years of language acquisition (and therefore, of life), can cause a significant underexposure to the linguistic environment. However, neural signatures that are typical of hearing individuals, can be also achieved later in life by deaf L2 learners. Hence, auditory deprivation, not necessarily translates in linguistic deprivation, if an L1 was developed. Children who falls under this risk of a severe linguistic underexposure in their first years of life, are at risk of developing a significant delay in language acquisition compared to their age peers. This emphasize the importance of fundamental and applied research on deafness condition as well as the crucial role that scientists have in their work of disseminators not only within the scientific community but also with parents of deaf children.

To summarize, we know that congenitally/prelingually deaf children are at risk of developing a delay in their linguistic performances, especially when they grow up in a hearing environment (i.e. born from hearing parents). However, if exposed to a rich linguistic environment, these children are able to reach good linguistic skills in the first language that they developed. Moreover, we will see that when they are implanted early in life, before the cut-off of the critical period for language acquisition, they showed good linguistic performances both in comprehension and expression scores. Therefore, there's not a direct link between deafness and language delay in which the first directly causes the second. As we know, the brain is highly prone to plasticity and given the exposure to a rich linguistic environment in which we are immersed, it is likely to be exposed to linguistic stimuli of some nature. Though, given the complexity of the linguistic information, it is crucial to maximize the exposure of deaf children to language and to support them in the process of the acquisition of a first language. Deafness and hearing impairment themselves do not directly lead to language delay. In fact, it is the underexposure to language (independently of the modality), which is what causes linguistic development delay.

1.1.3 – Late deafness and cognition – Language

Late deafness onset is the main sensory disability during ageing that has been associated to cognitive decline (Lin et al., 2011, 2013). Despite late deafness does not affect the development of cognitive functions, it constitutes nonetheless a major change in sensory experience and, as such, it can impact on cognition. How does a auditory deprivation occurring after childhood affect cognitive functions like language? Late deafness is not highly represented in the literature about language, but it represents a population of interest for several reasons. As previously anticipated, it represents a very large portion of the population with an estimation of at least 20% of the population developing some degree of deafness at some point along the lifespan (Abutan, Hoes, Van Dalsen, Verschuure, & Prins, 1993). Hence, this portion of the population can suffer from many deafness-related problems like social exclusion and isolation that can consequently contribute to severe cases of depression (Hogan, 2001). From a linguistic point of view, severe and profound deafness emerging later in life, can also have a strong impact despite language has already been entirely or partially acquired. In this manuscript, we used the limit of 3.5 years old for profound hearing loss onset to distinguish between pre/peri-verbal from post-verbal deafness. After becoming deaf later in life, when the hearing aids became insufficient, cochlear implantation has become a valuable option. Late deafness onset can impact language in many different ways with the performances in listening and production being commonly among the most affected (Cowie & Douglas-Cowie, 1983) whereas, grammar and reading skills tend to remain at a pre-deafness baseline. Therefore, postlingually deaf individuals can be considered an interesting control group for the prelingual population. These two groups share some features (i.e. deafness onset etiology, etc.) while others aren't in common (i.e. hearing duration as a function of language proficiency). Moreover, the late deafness group also needs to be thoroughly investigated because it can be useful to better understand the impact of late sensory deprivations on cognitive functions such as language.

1.2 – Introduction to deafness and Cochlear Implants

Sensorineural profound deafness has found in the modern medicine a treatment that can partially restore the auditory input: Cochlear Implant (CI). If the importance and the reach that this biomedical device has achieved over the past 30 years has been acknowledged by many (Wilson, 2013 among others), short-them and long-term outcomes still represent a matter of investigations. While many implanted individuals faced a good recovery after surgery, many others did not find the same successful outcome both in terms of sounds processing and language recovery (see for example Moberly, Bates, Harris, & Pisoni, 2016). It is easy to be misled by the amount of researches that are focused on the study of good after-implant performers, while those who experienced a bad outcome therefore displaying a low efficacy of the CI are frequently under-represented (see Pisoni, Kronenberger, Harris, & Moberly, 2018 for a comprehensive review and discussion on the difference between efficacy and effectiveness after implantation). Cochlear implant added an entire new variable that we usually refer to as -age at first implant-. The time between deafness onset and the age at first implantation represents a critical period for each individual in that situation.

In recent years, parents of deaf children are usually advised to proceed with a very early implantation, that has been proven to be very important for a good outcome after surgery. At the same time though, early implantation also carries rare but possible surgery-related risks (i.e., mild/severe flap infection, cholesteatoma, persistent eardrum perforation, flap swelling, hematoma etc.) (Bhatia, Gibbin, Nikolopoulos, & O'Donoghue, 2004). As we will further discuss, cochlear implant should be considered as a viable and often effective solution, always keeping in mind its limitations both in terms of the quality of the signal and for linguistic recovery.

1.2.1 – What are Cochlear Implants and how it differs from hearing aids

Cochlear Implant (CI) is a relatively new auditory neuroprosthesis that transmits acoustic waves coming from the external environment to the acoustic nerve bypassing the middle ear as well as any damage to the cochlea (Kral & Sharma, 2012). CI is therefore used as a treatment for bilateral profound sensorineural hearing loss (Copeland & Pillsbury, 2004). On the other hand, conventional hearing aids are basically amplifiers that include a microphone to receive sounds, boost the level of the signal by applying filters that are tuned to the recipients (National Research Council, 2004). Even though, this short description represents a huge simplification of the variety and the complexity of such devices, it clearly depicts the core differences from cochlear implants. The aim of the hearing aids is to take advantage of any residual hearing whereas cochlear implants restore hearing experience when deafness is profound. To date, with more than 20 years of clinical applications, cochlear implants has been defined as one of the most successful bio-medical devices ever created for the treatment of a sensory loss.

The working principle of cochlear implants is relatively straightforward: the soundwaves are encoded by an external microphone mounted on the ear. The sound is then processed by the processor and digitized according to the mapping and the strategy of the specific manufacturer and configuration. The digitized sound is then sent to a coil magnetically attached on the scalp which convey the information to the implant receiver under the skin, engraved in the skull. The implant transforms the digital signal in electric impulses that travel along the electrodes array inside the cochlea where the impulses are then transmitted directly to the acoustic nerve. At that point, the acoustic signal, is sent to the primary acoustic cortex where it will be processed and routed to the many different areas of the brain.

1.2.3 – What does Cochlear Implant allow to perceive?

It is rather common in a non-specialized environment to find the misconception that cochlear implant does completely restore the auditory system allowing former deaf recipients to hear again, effortlessly. In fact, the acoustic experience immediately after cochlear implant activation requires time, training and effort to reach a socially relevant level of understanding in situations like speech in noise understanding, prosody and voice identification, etc. (Barone & Deguine, 2011). Every individual, after being implanted have to develop a strategy that allows him/her to increase the signal to noise ratio with speech and relevant sounds being the signal to be isolated from the non-relevant noise. This primary focus makes CI users better sounds categorizers rather than sounds identifiers with CI users performing better in category identification rather than in token-sounds identification (Inverso & Limb, 2010). Recently, a group of researchers demonstrated the importance of the rehabilitation immediately after implantation in post-lingually deaf adults, showing for the first time how the categorization develops through time. Specifically, they showed that there is an improvement in the first six months after implantation for the categorization of vocal sounds with respect to non-vocal sounds. They also proved that the acoustic cues used by patients differs along the rehabilitation process. Specifically, at the beginning they used the so called “acoustic listening” where features like pitch, loudness and timbre are the qualitative aspects extracted from sounds. At the end of the rehabilitation, they started to show a gradual shift toward the “everyday listening” in which *“information about the meaning of objects in the environment and their actions are extracted”* (Strelnikov et al., 2018). As the authors highlighted, it is still a matter of interest to further investigate the mechanisms behind the strategies of recently implanted deaf individuals. The fact that CI users encounter substantial problems with the identification of environmental sounds has been proven by comparing them with normal hearing controls as well as by demonstrating that, after an intensive training, performances can be improved by a significant degree (Shafiro, Sheft, Kuvadia, & Gygi, 2015). To date, most of the rehabilitation practices focus on the improvement CI users’ abilities in the discrimination and processing of linguistic stimuli. Despite this makes sense from a social perspective, it does create an unbalance toward language at the expenses of sound localization, sound recognition, etc. To date, a significant effort has been made to improve the intelligibility of speech in noisy environments (Gopalakrishna, Kehtarnavaz, Mirzahasanloo, & Loizou, 2012; Liu et al., 2013) but less was done for environmental sounds intelligibility and recognition. These works both by enhanced the speech spectrum of frequencies by favoring a specific angle of sound source in front of the person assuming that most of the time the speaker stands in front of the listener. Therefore, controlled situations like speech therapy, can benefit from this unbalance and it is good in order to maximize the ability of CI users to start creating the associations between sounds and letters/words. However, it does not translate well in the real world where people are immersed in a full spectrum of sounds that includes speech as well as environmental relevant and irrelevant noises. Implanted children did not show any correlation between their improvement in language perception and their ability to discriminate environmental sounds and one of the suggested solution was to maximize the exposure of these children to everyday sound situations by including this practice in the rehabilitation programs (Liu et al., 2013).

Although we reported a strong and reasonable unbalance toward speech and language rehabilitation in cochlear implant recipients, the recovery of speech recognition doesn’t mean that CI users are good in the discrimination of voice features. Massida and colleagues (2013), showed difficulties in gender discrimination by CI users when compared to normal hearing controls (Massida et al., 2013). Fuller et al. (2014) suggested that this could be explained by the prioritization of CI’s processors for fundamental frequencies (F0) related to vocal pitch cues rather than a good balance of F0 itself and the information about the length of the vocal tract (Fuller et al., 2014). Gender discrimination difficulties can have a negative impact on social well-being and integration, but it can be partially contrasted thanks to inputs coming from intact sensory systems, primarily vision. Where visual integration is limited though, is in the emotion detection and discrimination, with cochlear implanted people being more influenced by incongruent facial expression during an auditory task where they had to judge acoustically delivered emotion stimuli (Fengler et al., 2017). All of these aspects contribute to the quality of life perceived by CI recipients. Emotion detection for example, has been demonstrated to be a strong predictor for quality of life, measured with the NCIQ (Nijmegen Cochlear Implant Questionnaire) in postlingually deaf cochlear implant users (Luo, Kern, & Pulling, 2018). As previously mentioned, cochlear implants adopt filters and strategies that can and should be finely tuned to become more accurate in delivery better voices information in the upcoming future (Agrawal et al., 2013; Chatterjee et al., 2015).

Besides, a growing branch of the research on cochlear implants is trying to better understand how cochlear implant users perceive the location of sounds with unilateral or bilateral implants. Specifically, some postlingually deaf CI users can discriminate right versus left sound location, but half of them struggle with a more complex array of loudspeakers (Litovsky, Parkinson, & Arcaroli, 2009). They also found a relationship between measures of sound localization and performance on a speech intelligibility task: bilaterally implanted participants who were able to better localize sounds, were also able to make better use of speech information in the presence of competing multi-talker babble (Litovsky et al., 2009). Along with other researches (e.g. Pavani et al., 2016), this argument is often used to support benefits for bilateral implantation.

1.2.4 – Cochlear Implant and critical period

In the field of early sensory deprivation, the risk of insufficient input during a period of brain development has always raised a strong interest. This period, when an infant develops crucial cognitive function such as language, has been called critical/sensitive period. Usually, these two terms are used to define a limit in time after which the acquisition and the learning processes are harder than they were before the limit of the -*critical period*-. In the field of deafness and sensory losses in general, the critical period refers to the limited time in which, mechanisms like neural/cortical plasticity are still possible. In congenital hearing loss or in perinatal deafness, with the cochlea still capable of receiving electric stimulation, it is possible to resort to cochlear implant in order to partially restore the functionality of the auditory pathway of the recipient. By restricting the cases to congenital deaf children, the questions that arises are the following: when is it better to implant? Is there a limit over which, cochlear implantation brings limited advantage?

A. Kral and A. Sharma hypothesized that there are several reasons why there is a sensitive period and why it is limited in time (Kral & Sharma, 2012). Synaptogenesis, for example, is a mechanism that works along the entire lifespan (Holtmaat & Svoboda, 2009), and by being stronger in the very early stages of life, it also happens in sensory deprivations, with new routs formation with the unused cortex. If these formations are not guided by the typical needs of the considered cortex, the new routs may not go in the direction of the typical auditory pathway and therefore, can be non-positively functional to the aim of restoring the auditory functions. The presence of functionally altered networks after unguided synaptogenesis and pruning, was found in cats (Kral, Tillein, Heid, Hartmann, & Klinke, 2005). Kral and colleagues (2005) also reported that later in life and therefore, after the closing of the critical period, corticocortical interactions are limited and less prone to modulations. These arguments and results collected from both deaf children and animals are consistent and point toward the existence of a sensitive period in children who are born deaf. Therefore, early cochlear implantation within the sensitive period is suggested in order to take advantage of neural plasticity in the auditory network (Kral & Sharma, 2012).

To corroborate their claim, they showed results form a longitudinal study that involved a large group of prelingual deaf children implanted in different stages of their childhood using cortical auditory evoked potentials (CAEPs). Results were rather straightforward, with children implanted earlier in life (before 3.5 years) showing the early cortical response (P1) becoming more similar to hearing peers. On the other hand, with the increase of the age at implantation, P1 responses started to become less comparable to early ERP responses recorded from normal hearing controls showing a weaker recovery after CI activation. In the end, they suggested that cochlear implantation is better when it was done before the age of 3.5/4.0 years, with even better results before the age of 2 years. Instead, implantation after 6.5/7.0 years does not allow optimal cortical maturation in response to auditory reafferentation (Kral & Sharma, 2012).

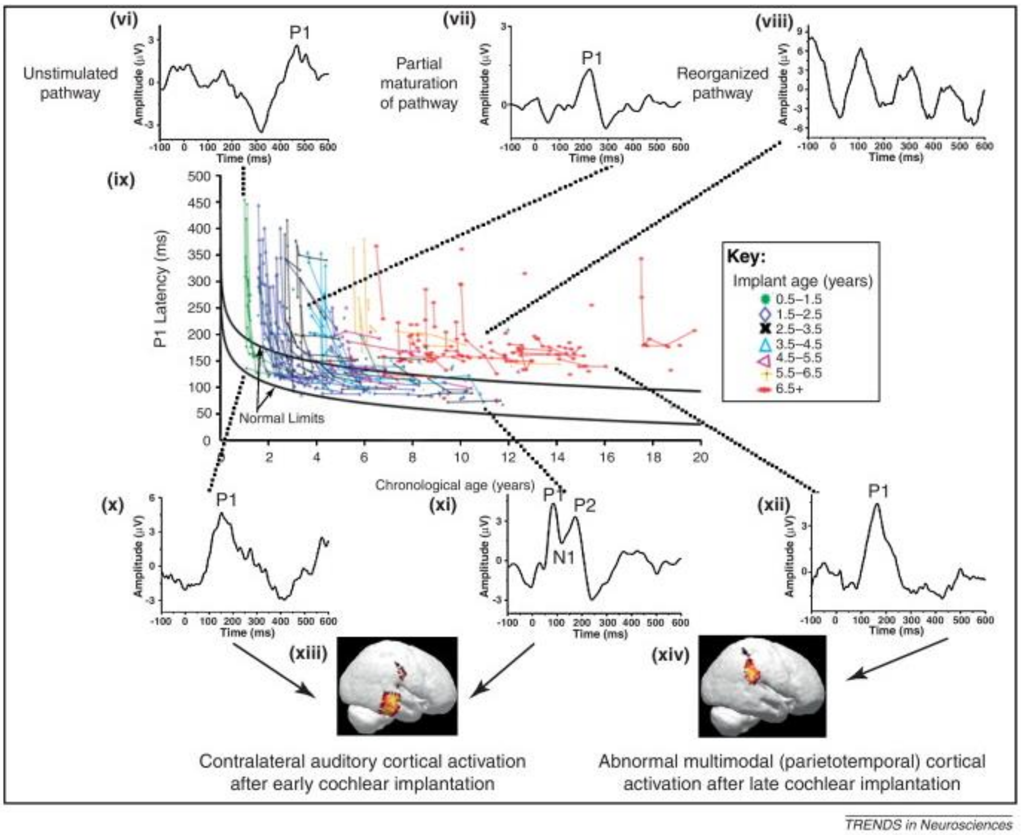

Figure 1.1 – *CAEPs (Cortical Auditory Evoked Potentials) longitudinally recorded in children at different ages (x axis) represented by each line. Color refers to different ages at implantation from 0.5 years up to 6.5 + years of age. Black lines represent the normal limits where typically developed young individuals typically stand. On the y axis, the P1 Latency expressed in milliseconds.*

From: *Developmental neuroplasticity after cochlear implantation.*

This result heavily impacted the perception of the discussion around the sensitive period as well as it impacted the clinical practice with early implantation becoming more and more common around the world. Although the result is supported by many studies and it is in line with what we know about the biology of the brain, it often has been misinterpreted and erroneously used in support of early implantation from a linguistic point of view. Neither the intention (find the best time window for implantation), nor the methodology (CAEPs) used in the aforementioned study are specifically tuned for language and as such should be considered. When we say that there is a critical period for language acquisition, we assume that there is a range of time after birth, in which deaf newborns, if exposed to language, can acquire an L1 avoiding being left far behind hearing individuals. Therefore, if the aim is to test linguistic capabilities after early implantation compared to late implantation, more complex linguistic stimuli should be employed. Furthermore, it is crucial to rely on well-known linguistic EEG components.

The work of Andrej Kral and Anu Sharma (2012) represents a good starting point that showed, with a very elegant paradigm, the existence of a sensitive period for neural plasticity in congenitally deaf children. That represented a crucial starting point for our aim to test the effect of cochlear implantation across that critical period by using a combination of complex linguistic stimuli and well-established linguistic ERPs. Critical period for language acquisition and development will be discussed in a dedicated paragraph.

1.3 – Cochlear implant and language

Cochlear Implant can restore auditory input in profoundly deaf individuals. Therefore, it has a huge impact for language acquisition, development and processing. It also adds a significant variable in the landscape of deaf study with the *age at implantation* (that usually refers to *age at activation*), *deafness duration before CI*, *CI usage duration*, becoming relevant factors in the analyses. As we will discuss in the section below, cochlear implantation has been proven to have better results for spoken language when children are implanted very early in life, particularly when surrounded by a rich and supporting environment (McConkey Robbins, Koch, Osberger, Zimmerman-Phillips, & Kishon-Rabin, 2004; Svirsky, Teoh, & Neuburger, 2004). Cochlear implantation can induce a strong mechanism of restoration of the typical auditory network which again, is strongly dependent on the age at implantation as we will see in many works in the literature both on primary cortical responses (e.g. Kral & Sharma, 2012) and on language (e.g. Niparko et al., 2010).

1.3.1 – Language development in preverbal cochlear implant users

Thanks to the work of Kral and Sharma (2012) we have been able to see how impactful CIs can be for the development of primary auditory cortices, especially if they are made in a very early stage of life. On the other hand, many studies have investigated the impact of CIs from a linguistic point of view. John Niparko and colleagues (2010), showed that children implanted early in life exhibited better than expected performances in oral comprehension and production. In particular, the authors showed the trajectories of children implanted before the age of 18 months, between 18 and 36 months and after 3 years. Developmental trajectories were closer to the normal range of control subjects and showed less interindividual variability when implanted before 18 months. Performances and variability increased in the second group (age between 18-36 months) with the last group (age > 36 months) performing the worst and showing the widest variability between subjects (Niparko et al., 2010) (see Figure 1.2).

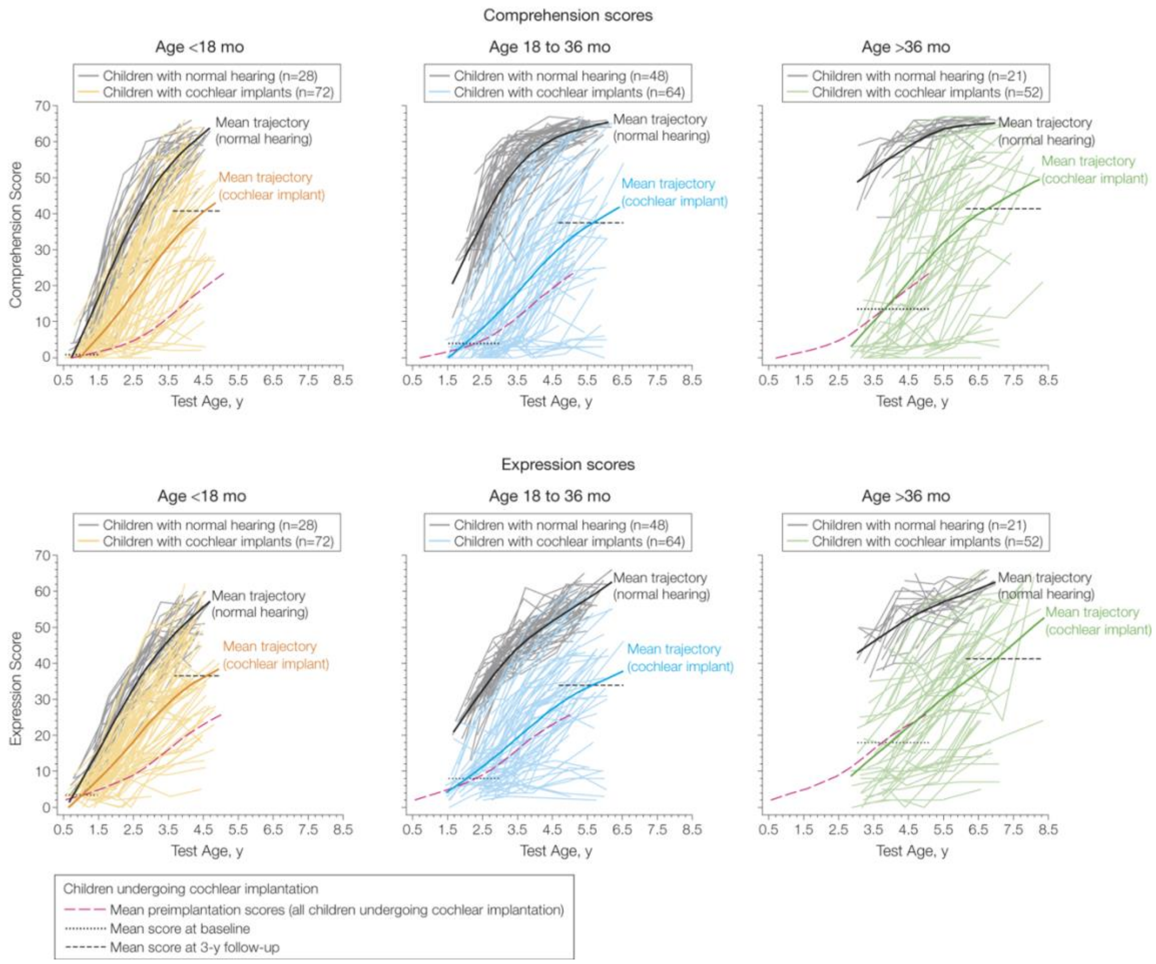

Figure 1.2 – *Comprehension (above) and expression (below) scores of implanted children each represented by one line. Children were repetitively tested ad different ages (on the x axis) with the vertical axis representing the score. Gray lines represent normal hearing controls, colored lines stand for CI users implanted within different age ranges: before the age of 18 months (in yellow), between 18 and 36 months (in blue) and lastly, implanted after the age of 36 months (in green).*

From: *Spoken Language Development in Children Following Cochlear Implantation.*

Many other studies investigated how cochlear implant can help children to achieve a good linguistic level. If the cochlear implant is provided before the critical period for language acquisition which is commonly established to be at around 3.5/4 years, the outcome of linguistic skill is likely to be positive and on average, better than those who maintained a limited or absent acoustic input (Geers, Davidson, Uchanski, & Nicholas, 2013; Nicholas & Geers, 2006; Niparko et al., 2010). Overall, many researches seem to agree that early implantation should be privileged over implantation later in life. In a study that came out in 2002, children implanted before the age of five years were tested before implantation and re-tested after 6 months from the activation of the CI. Among these children, those implanted before the age of three, showed better communication skills (Kirk et al., 2002). However, what is the long-term effect of early implantation? Is the difference in performances between early and late CI users lasting also later in life? Dunn and colleagues tested more than eighty prelingual deaf children divided in early (< 2 y.o.) and late (between 2 and 3.9 years) CI adopters, aiming to test their speech perception, language, and reading abilities in a longitudinal study. Their results confirmed that early implantation (before the age of four) is better for language development. However, they also stated that the variable of the age at implantation does actually fail to explain the variance in the linguistic performances with the increase of the age at implantation once the critical period is over. Specifically, when tested between the ages of 7 and 13, differences between the two groups (early vs. late CI adopters) started to become non-significant (Dunn et al., 2014). Although age at implantation is not the only one variable that should be considered, it explains a rather relevant portion of the variance (14.6%) when the performances for expressive language were compared in children who received the cochlear implant in infancy (before 15 months) and those who received the CI after the age of 18 months, with the latter showing less rapid growth of the curve (J. Bruce, Barker, Spencer, Zhang, & Gantz, 2005). Again, early implantation is showing its good potential when Geers and colleagues showed that in several linguistic measures, all young participants who received the CI early in life, performed better than those belonging to the late implanted group. They also showed that among early implanted children, roughly 50% of them, showed age-appropriate scores in receptive and expressive vocabulary, receptive and expressive language and in verbal intelligence (Geers, Moog, Biedenstein, Brenner, & Hayes, 2009). Reading skills being better in early implanted children has also been proved in another study where children implanted before the age of 42 months showed normal hearing progression in reading abilities (Archbold et al., 2008). Although early implantation seems to be better than late implantation, this is not always true and the variability in the performances within the group of early-implanted tested participants should be more thoroughly investigated (van Wieringen & Wouters, 2014) with the authors suggesting to put a greater effort following existing guidelines (Yoshinaga-Itano, 2014) in order to expand the knowledge in the field of early implantation. This kind of results showed the *efficacy* of cochlear implantation where efficacy refers to *"the ability of an intervention to produce the expected results in a single individual"*. Therefore, none of these results are actually trying to reveal the *effectiveness* of cochlear implantation. Effectiveness, contrary to "efficacy", refers to *"the ability of a treatment to produce the desired effect for a person in the real world"* (Pisoni et al., 2018). Although very subtle, this distinction in very important to better interpret results and discussions of works that are involving not only deaf CI users, but also others clinical populations, as well as any training program.

To summarize, if there is one result that is consistent across different languages is that the sooner the cochlear implant is done (preferably before 2-3.5 years of age) the more a positive outcome becomes likely. Though, many of those studies are based on the oral performances and in particular on oral comprehension and/or oral production (Nicholas & Geers, 2006; Geers et al., 2013; Geers et al., 2013) whereas to my knowledge, a few behavioral studies has been conducted with reading or writing tasks (e.g.: Geers, 2003).

Studies in Italian follow the same direction of results showing overall better linguistic development in early cochlear implantation. The activation of the CI in the second year of life can help children (tested at a mean age of 54 months) to reach a good if not comparable linguistic level of normal hearing peers testing lexical and morphosyntactic skills in comprehension and production, while still showing limitation in phonological abilities after 3 years from implantation. In particular, Caselli and colleagues (2012) showed that the CI users keep pace or exceed NH children when they are matched for time since the CI was activated for language acquisition while performing significantly worse than age peers for lexical comprehension. A strong variability between subjects were also found in grammar evaluation where some CI children performed significantly worse than age peers while others passed the level of their chronological age (Caselli et al., 2012). Again, even though the efficacy of early implantation has been repetitively proven for linguistic skills, dedicated speech therapy intervention should be at the core of the post-implantation procedures allowing deaf implanted children to overcome the difficulties in social experiences and interactions mediated by language (Rinaldi, Baruffaldi, Burdo, & Caselli, 2013).

Chapter 2

2.0 – The study of language processing through EEG

2.1 – Language and psycholinguistic electrified

Language is among the most researched and investigated domains of the human brain and it has been studied with a wide variety of techniques. In the common knowledge, language and the ability to communicate with such a degree of complexity, is what differentiate humans from animals. Language can be studied from a variety of point of view: from the most linguistic to the most biological oriented. From a neuroscientific point of view, language is probably one of the most transversal domains of the human mind. Not a single system in the brain is disentangled from language. Motor system, memory, attention, vision, are all connected to language. Language is also the main tool of humans to initiate and maintain social interactions and for each individual to develop his/her role in the world in which we are immersed. We can study language with many different techniques: EEG for an online measure, fMRI for the localization, MEG for frequency related analyses and behavioral measures to test a wide variety of manipulations without being limited to techniques that have limitation for special populations.

2.1.1 – The origin of language research with EEG

Among all of the aforementioned techniques, language is often studied through electroencephalography (EEG). EEG is a relatively cheap technique, especially when compared to the magnetoencephalography (MEG) and it represent a useful tool to study language processing.

Language is composed by discrete units such as phonemes, words and sentences. Sentence level psycholinguistics aims to understand how words and morphemes are integrated into larger meaningful units such as phrases and sentences during production and comprehension. Since listening or producing a sentence requires a very short time (some seconds) in which some process is assumed to cyclically repeat at each word, the requirement of experimental techniques with a fine time resolution is particularly important.

Despite off-line techniques have been used for the study of sentence processing, they have the disadvantage to lose the ability to detect which specific points raise specific difficulties in comprehension. For example, an acceptability judgement task at the end of a sentence (competence) can give us useful information about the ability of participants to understand the meaning of a sentence but grants limited access to the way in which the brain and the cognitive system arrived at the response. Despite paradigms like self-paced reading (Just, Carpenter, & Woolley, 1982) and eye movement tracking (Sereno, 2003), can solve part of the problem by measuring behavioral costs during reading, it still lacks to qualitatively disentangle possible differences in the nature of the difficulty. It has been shown that the use of event-related potentials (ERPs) can solve the problem by providing continuous online information during sentence processing and by associating events (single words and position within a sentence) to specific and recognizable components of the EEG averaged across a number of repeated trials. Therefore, not only there is the ability to record a continuous signal, but we are also able to time-lock controlled events linking them to the underlying physical or mental occurrence (Picton, Bentin, & Berg, 2000).

When these potentials are in form of reoccurring voltage fluctuations that become systematically associated to some specific manipulation are called *components*. These components are the phenotypic representation of the neural activity of underlying neural processes and networks (Näätänen & Picton, 1987) and proved very useful in the study of language processing. We will analyze the main components linked to language like the N400, the LAN and the P600 thanks to which we have been able to probe semantic and syntactic processing during sentence comprehension, as well as we are allowed to speculate the timing of the access to the meaning of a word and when it gets integrate in the sentence from a meaning and syntactic point of view.

2.1.2 – Most investigated components and their functional interpretation

One component that has been extensively linked to language was described for the first time in 1980. Kutas and Hillyard (1980) were in fact the first to report that during sentence processing a negative fluctuation was systematically measured in in correspondence to a semantic violation such as the last word of a sentence like "He took a sip from the transmitter" with respect to the control condition "He took a sip from the glass" (Kutas & Hillyard, 1980). The N400 is a negative deflection that peaks around 400 ms after the onset of the critical stimulus (transmitter/…) that does not match in meaning with the rest of the sentence. The N400 has a typical central distribution. This component has been linked to language after observing a systematic deviation from the typical P300 (component associated to the violation of expectancy) when the violation occurred in a linguistic context. After decades of corroboration, the N400 has become widely accepted to be linked to semantic access and integration effort (Kutas & Federmeier, 2011). Modulations in the amplitude of the N400 are mostly explained by the cloze probability (the degree of expectancy of a word given the context). This variable, usually measured by filling the blank off-line tests, inversely correlates with the amplitude of the N400 (Luck, 2014). Modulations of the N400 have been linked to the frequency of a word. Words that are more frequent, are often linked to smaller N400 amplitude and vice versa (Dufau, Grainger, Midgley, & Holcomb, 2015). Further studies showed that the N400 is not only associated to semantic integration difficulties within sentences. Instead, priming effect was found to be also linked to the typical N400 negative component (Bentin, 1987). This component can also be elicited in experiments with pictures instead of words (Ganis & Kutas, 2003; Nigam, Hoffman, & Simons, 1992; Pratarelli, 1994).

If the increase of the N400 component is commonly associated to difficulties in in lexical and semantic retrieval and integration, the P600, has been associated to syntactic difficulties. The P600 has been discovered in 1992 by two researchers who asked participants to read sentences where one element was syntactically wrong (i.e. "The broker persuaded to sell the stock"). In this case, they observed a positive deflection in between 500 and 1000 milliseconds after the word *"to"* was presented. The same preposition did not elicit any component when it was embedded in a congruent context like for example in *"The broker hoped to sell the stock"* (Osterhout & Holcomb, 1992). The P600 has been often associated to another component that has a negative peak between 300 and 500 ms with a left-frontal distribution called left-anterior negativity (LAN) (Angrilli et al., 2002; De Vincenzi et al., 2003; Hagoort & Brown, 2000; Molinaro, Barber, Caffarra, & Carreiras, 2015; Molinaro, Vespignani, & Job, 2008; Molinaro, Barber, Pérez, Parkkonen, & Carreiras, 2013; Molinaro, Vespignani, Zamparelli, & Job, 2011; Osterhout & Holcomb, 1992; Osterhout & Mobley, 1995). Violations of grammatical rules usually elicit what has been called a biphasic pattern formed by two consequent deflections with different polarities and topographies: the LAN and the P600. It has been proposed that the left anterior negativity reflects the failure to find a matching agreement constituent to which the word can bind (Bickerton & Szathmáry, 2009) or, it could be linked to an early stage of the violation of expectancy for a certain agreement (Mancini, Molinaro, Rizzi, & Carreiras, 2011; Maurer et al., 2006; Molinaro, Barber, & Carreiras, 2011; Steinhauer, Pancheva, Newman, Gennari, & Ullman, 2001). However, the LAN cannot be only associated to agreement violations since other linguistic manipulations can elicit or modulate this component (Molinaro, Canal, Vespignani, Pesciarelli, & Cacciari, 2013; Van Der Meij, Cuetos, Carreiras, & Barber, 2011).

The P600 is usually associated with agreement violations and several studies found the P600 in response to violations of the number-agreement between the subject and the verb in English (Osterhout & Mobley, 1995), but also in Dutch (Hagoort & Brown, 2000; Hagoort, Brown, & Groothusen, 1993), in Italian (Balconi & Pozzoli, 2005; Molinaro, Vespignani, et al., 2011) and in Spanish (Carreiras, Salillas, & Barber, 2004) but also in many other languages. The distribution of the P600 on the scalp shows generally larger amplitudes over posterior electrodes and even though some authors also reported frontal activations ascribable to the P600 (Friederici, Steinhauer, & Pfeifer, 2002; Kaan & Swaab, 2003). Although the P600 is systematically elicited by the presence of a grammatical error, the component should not be exclusively associated to violations, since it is also elicited by grammatical complexity. Some authors agree that the P600 should be interpreted *as a late stage of reanalysis that could operate on qualitatively different sources of information* (Bornkessel-Schlesewsky & Schlesewsky, 2008; Kuperberg, 2007; suggested in: Molinaro, Barber, et al., 2011). Molinaro et al. (2011) suggested that it could be possible to distinguish the P600 in two separate stages: an early and a late P600 (for similar arguments see Barber & Carreiras, 2005; Carreiras et al., 2004; Hagoort & Brown, 2000; Kaan & Swaab, 2003; Molinaro et al., 2008). The first would have a broader distribution also involving frontal areas of the scalp, it is usually present in the time window between 500 and 750 ms and would represent difficulties in the integration of the constituent with the rest of the sentence (Kaan, Harris, Gibson, & Holcomb, 2000). On the other hand, the more classic central-posterior distributed P600 in the time window between 750 and 1000 ms would represent the reanalysis and repair processes (Barber & Carreiras, 2005; Carreiras et al., 2004; Molinaro et al., 2008). More recently, Kasparian et al. (2017) proposed a 3-stage split of the P600 on the basis of differential effects of attrition on the ERP correlate of subject-verb violations in Italian. The debate around the Biphasic pattern LAN + P600 though is still open on another front that will be better explain in the introduction of Chapter 5, but it is worth mentioning here as well. Specifically, the open debate focuses on the existence of the biphasic pattern itself. Some authors challenged the existence of the biphasic pattern by hypothesizing that there is no P600 and LAN but instead a superposition of positive responders and negative responders with some people responding with an N400 and some other with a P600. By averaging the waveforms across subjects, the LAN + P600 effect, would emerge as the result of the sum of the two between-subject activations (Tanner, 2014; Tanner & Van Hell, 2014). For a deeper review of the debate on the left anterior negativity between Tanner, Van Hell (Tanner, 2014; Tanner & Van Hell, 2014) and Molinaro (Molinaro et al., 2015; Molinaro, Barber, et al., 2011).

2.1.3 – EEG Sentence processing in deafness and CI

The relationship between deafness and sentence processing has also been studied through electroencephalography and event-related potentials. The ability to accurately time-lock brain activity to controlled manipulation can help provide a substantial contribution to the knowledge on deafness and cochlear implantation. Despite some of the fine debates on the functional interpretation of ERP components are still unsolved, both the N400 and the P600 are considerate to be well-established EEG components for semantic and syntactic processing respectively. To date though, some of the more relevant work on the study of deafness and cochlear implantation through EEG, used either low-level linguistic stimuli (i.e. syllable /ba/) measuring cortical auditory evoked potentials (Roland, Henion, Booth, Campbell, & Sharma, 2012; Sharma & Campbell, 2011; Sharma & Dorman, 2006; Sharma, Dorman, & Spahr, 2002a, 2002b; Sharma, Spahr, Dorman, & Todd, 2002) or single-words linguistic aspects (Geers et al., 2013).

Deaf participants have also been studied with ERPs at sentence level. Mehravari and colleagues (2017), tested deaf adults without cochlear implant aiming to better understand similarities and differences in how deaf and hearing adults read. They asked deaf participants and normal hearing controls to silently read sentences containing semantic violations, grammatical violations or the combination of the two violations. Violations embedded in auditory and written sentences have been extensively proven to produce typical ERP components. Specifically, the N400 has been linked to semantic incongruities (Kutas & Hillyard, 1980) and the P600 has been linked to morphosyntactic violations (Osterhout & Holcomb, 1992). The experiment implemented a classic RSVP (rapid serial visual presentation) paradigm, in which participants were asked to carefully read the stimuli, delivered one at a time on a computer monitor, and to judge their acceptability at the end of each sentence. The results failed to detect a P600 effect in deaf individuals, while the typical positive shift at 600 ms was found in the control population as an indication of a neural signature of syntactic anomaly detection. By contrast, no difference between the two groups emerged in the N400 component, with both groups displaying comparable negative components at N400 ms after the critical word was displayed (Mehravari, Emmorey, Prat, Klarman, & Osterhout, 2017). This result corroborates the behavioral findings of a stronger impact of deafness on syntactic aspects of language processing than on semantic ones.

Children born deaf or became deaf in the very first months after birth, may pursue language acquisition through different modalities. The debate whether different modalities of language acquisition lead toward the same linguistic outcome is still open. However, the exposure to early linguistic experience independently from the modality (i.e. early signers), allows children to develop language within a normal range (Lyness, Woll, Campbell, & Cardin, 2013; Mayberry, Chen, Witcher, & Klein, 2011; Neville & Bavelier, 2007). The assumption that language processing does not depend on the acquisition modality, is also supported by studies that showed comparable ERP results in deaf participants. Skotara et al. (2011) showed that both deaf signers (L1) who learned oral German as an L2 and normal hearing L2 learners of German found typical N400 followed by a late positivity elicited by semantic incongruities and a posteriorly distributed P600 in response to syntactic violations during a sentence reading task. This experiment found an important result in support of the theory that language is modality-independent by showing that *“intra- and crossmodal L2 acquisition involve comparable neural systems”* (Skotara, Kügow, Salden, Hänel-Faulhaber, & Röder, 2011). ERPs have also been used by Hahne et al. (2012) with postlingual cochlear implant users that have been tested with auditory material, with the aim to to get insight into sentence comprehension mechanisms and specifically, to test whether patients and normal hearing participants share the same cognitive processes during sentence comprehension. Interestingly in the implanted population, although restored, linguistic signature like the late positivity showed to be affected by degraded input conveyed by cochlear implant. In particular, the N400 was typically elicited in the experimental group with a higher latency compared to hearing controls whereas the P600 was absent in the population of the CI users. Again, these results seem to indicate that an impaired auditory input can have a stronger impact in the syntactic integration process rather than on semantic processing. (Hahne, Wolf, Müller, Mürbe, & Friederici, 2012). As the authors themselves suggested, this population showed the value of late components for the study of language in cochlear implant recipients.

3.0 – Objectives, overview and methods of the present thesis.

3.1 – Introduction

So far, we have seen the impact that deafness can have in the life of auditory deprived individuals both from a social and a linguistic point of view. Although it does not represent the only solution, cochlear implantation proved to be a viable and valuable way to treat deaf individuals. As I previously discussed, many studies aimed to investigate the role and the impact that both deafness itself and cochlear implantation have on auditory processing and language acquisition and development. Despite this represents an active frontier in the field of studies on sensory deprivations, we aim to add valuable information to an already widely discussed topic that still lacks to comprehensively describe the impact of implantation in pre- and post-lingually deaf individuals. In fact, a very small portion of the aforementioned studies do actually investigate written language processing with a technique that is capable of recording brain events while they occur providing very high time resolution such as electroencephalography (EEG).

While behavioral measures are very efficient in collecting a high number of data due to its good balance between the requested effort from both participants and experimenters and because of its relatively small needs of repetition to increase the signal-to-noise ratio, they are not built to record live activations originated from the brain. To this aim, we decided to adopt a well-established paradigm (see paragraph 3.2.3 for further details) specifically created for ERPs recorded via EEG. Briefly, we adopted written sentences provided visually one word at a time on a computer monitor. Half of these sentences were filled with either a semantic or a syntactic anomaly with the remaining half acting as fillers. Violations represented our target for the analyses where we compared violations with the respective control conditions aiming to find ERPs such as the N400 and the P600 in response to semantic and syntactic violations respectively.

Thanks to EEG we were able to record data coming directly from the scalp while the task was running, without having to exclusively rely on behavioral tasks. Moreover, the ERP approach allowed us to time-lock the electric signal with the target word. While not being an innovative approach, the combination of well-established paradigm and type of manipulation, electrophysiological technique and widely studied ERP components allowed us to have a strong well-rounded paradigm to work with.

However, one of the drawbacks of EEG and ERPs, especially if conducted on a special clinical population that is difficult to recruit, is the need of item-level repetition. Because what we are measuring thanks to the EEG, is a raw average of electric signal coming from many different sources inside the brain, we need to compute a grand-average of the signal coming from the same condition. This translates in a strong restriction of the manipulations that we could implement in our paradigm. Hence, we adopted a single type of syntactic agreement violation (number between the subject and the verb) as well as a strongly counterbalanced design for the semantic condition (see paragraph 3.2.1 for an in-depth description). For this reason, and also to have measures for correlations, we also adopted a wide variety of behavioral tasks (e.g. semantic fluency, grammaticality judgement, sentence picture matching, lexical decision, etc.). These behavioral tasks allowed us to widen the range of the type of manipulations that we could have tested as well as they allowed us to test different kind of tasks other than asking participants to provide an acceptability judgement at the end of each sentence during the EEG task. Combined, EEG-recording and behavioral measures represent a comprehensive way to test the impact of cochlear implantation on deaf individuals regardless of the onset of the sensory deprivation. Moreover, of course we also collected relevant personal and clinical information enriching even more the amount and the type of data that we have for each individual. Therefore, we can cluster data in three layers: 1) individual information, 2) behavioral and 3) EEG-ERP data. We will discuss in depth each layer for each single study providing in-depth analysis where needed as well as we correlated measures across layers both pre- and post-hoc in order to provide a more comprehensive interpretation of the results and to answer our hypotheses.

For us, it was important to rely on a strong and safe paradigm prior to collect data from the clinical group. Hence, we started to collect data from normal-hearing participants which would have been subsequently, a well-distributed sample of controls from which to draw subjects that match the age of each CI user. Thus, the initial sample of normal-hearing controls was large enough to also serve the purpose of being treated as a wide sample in order to test the reliability of our experimental conditions, both EEG and behavioral. Moreover, the distribution of the ages, ranging from 12 to 65, allowed us to think in advance at a specific grouping of the ages. Specifically, we decided to collect 48 participants equally distributed into 4 groups of twelve subjects each. By operating this clusterization in advance, we were then able to think at specific hypotheses for the control group alone given its weighted balance across a very wide range of lifespan.

To summarize, the study of the hearing control group resulted having three distinct purposes. First, it served as a validation group for both the paradigm and the sentences themselves, because despite being a common experimental design, all of the experimental items were created by us in Italian, following precise boundaries that will be shortly explained in the methods section below. Second, we were able to test the effect of age on the components of interest, which is something that is missing in the literature and that could be also relevant for the interpretation of the results in our studies with CI users. In fact, we will report interesting data coming from this study that leads toward the conclusion of a less monolithic interpretation of the P600 across the lifespan as already debated by Kaan et al. (2003). This kind of study can also prove to be very useful to expand the relatively small sample of studies in Italian providing valuable information to be added in one of the several debated that are still open around language-related ERP components and their interpretation. Third, it served as a pool of control participants to be quickly age-matched with CI users collected for both study 2 (pre-lingually deaf CI users) and 3 (post-lingually deaf CI users).

After the first study of hearing participants, we will describe our main study that involved prelingually deaf CI users compared to an aforementioned subsample of age-matched hearing controls. This study is crucial to our aims, since it involves people who were born deaf or who became deaf early in life (before the age of 4 y.) and who received a cochlear implant. Given the fact that none of our participants learnt sign language, we have a group of people who acquired and developed their language through their cochlear implant which means that we can investigate if and how cochlear implantation impacts language acquisition and processing from both an ERP and a behavioral point of view.

However, as we discussed in the first chapter, deafness does not necessarily affect people from birth or in the very first years of life. In fact, deafness onset is even more frequent to occur later in life with a wide spectrum of etiologies from which deafness can be attributed. While being less homogeneous, postlingually deaf CI users' group is also interesting to be studied. Our third study, while maintaining the same structure and design of the previous one, does have a different population and consequently, different aims. By studying this kind of population, we are asking ourselves how a CI impacts language processing in people who have already acquired the same language naturally, or at least passing the cut-off of the sensitive period for language acquisition. Compared to the previous study (involving prelingually deaf CI users) this study (postlingual CI users) can be treated as a further control condition for study 2 by also creating a continuum between study 1 (NH controls) and study 2 (prelingual CI users).

3.2 – Methods

All methods presented in the present chapter are valid for both the two studies involving CI users as well as for the study on NH-controls. While the majority of the apparatus, procedures and methodologies are the same across the three studies, should any deviation occur, it will be pointed-out accompanied by the motivation.

3.2.1 – ERP Stimuli

Our ERP sentences stimuli were 320 sentences arranged in 2 main groups: half of them were built to test semantic processing and half of them for syntax processing. Since we decided to adopt typical stimuli used to find well established ERP components such as the N400 and the P600, sentences were either semantically well-formed or contained a lexical-semantic anomaly; and were grammatically correct or contained a subject-verb number agreement violation. Therefore, 80 sentences had a lexical/semantic violation embedded (2); 80 contained a syntactic violation (4 a/b) and the remaining 160 were control correct sentences specifically tuned to balance the violated conditions (1, 3 a/b). All violations occurred on a critical word in the sentence which was never the last one. As mentioned, sentences in the syntactic condition were violated in their number-agreement with half of them having the subject singular and the verb plural and half of the opposite. Therefore, target words in the syntactic condition were always verbs since the expectation of the number was triggered by the subject at the beginning of the sentence.

CONDITION	**SENTENCES**
1) Semantic, well-formed	Sulla scrivania ho appoggiato una penna bianca.
	On the desk I put a pen white.
	[I put a white pen on the desk.]
2) Semantic, violated	Sulla scrivania ho appoggiato una <u>pecora</u> bianca.
	On the desk I put a <u>sheep</u> white.
	[I put a white sheep on the desk.]
3) Syntactic, well formed	a) Il presidente firma l'atto di pace.
	The president$_{[+s]}$ signs$_{[+s]}$ the peace act.
	b) I presidenti firmano l'atto di pace.
	The presidents$_{[+p]}$ sign$_{[+p]}$ the peace act.
4) Syntactic, violated	a) Il presidente <u>firmano</u> l'atto di pace.
	The president$_{[+s]}$ <u>sign</u>$_{[+p]}$ the peace act.
	b) I presidenti <u>firma</u> l'atto di pace.
	The presidents$_{[+p]}$ <u>signs</u>$_{[+s]}$ the peace act.

Table 3.1 - *The critical word for ERP averaging is underlined.*

Sentences from the syntactic condition were built starting from a stem well-formed sentence with singular subject and singular verb. Starting from that, all the combinations were made as follows: singular subject-singular verb (correct); singular subject and plural verb and vice-versa (agreement violation) and finally, plural subject and plural verb (correct). Each participant saw only one of the four sentences from each block of four to avoid having subjects that recognize the same meaning in two sentences throughout the session.

A different approach was used to build the group of four sentences for the semantic condition. One correct sentence (1) was built as a starting point and the violated one (2) was equal except for the target word. The target word must have had the same length (number of characters) and a similar frequency logarithm (within a value of 0.5 according to the "La Repubblica" corpus). To complete the quatrain, another correct (3) and violated (4) sentences following the same rules have been built with also their target words of the same length and frequency of the first two sentences. In this case, each participant saw 1 (i.e. "Quando sorge il sole la luce aumenta" ["When the sun rises the light increases"]) and 4 ("Se versi il volo il latte è più buono" ["If you pour the <u>flight</u> the milk tastes better"]) or 2 (i.e. "Quando sorge il <u>tappo</u> la luce aumenta" ["When the <u>cap</u> rises the light increases"]) and 3 ("Se versi il cacao il latte è più buono" ["If you pour the cocoa the milk tastes better"]) allowing us to have all of the stimuli counterbalanced without resorting to the Latin-square design which is an n × n array in which each item occurs exactly once in each row and exactly once in each column.

To validate the stimuli, a larger sample (202) of correct sentences of the semantic condition were tested for their acceptability. 40 random semantic violated sentences were included as a control condition. 71 participants responded online to a questionnaire where they were asked to judge the acceptability of 202 sentences on a Likert scale that ranged from 1 (meaning "not at all unusual") to 5 (meaning "very unusual"). We calculated the average response among the correct sentences (mean=

2.3904) and we considered items exceeding that value to be discarded from the employment in the main experiment. All of the violated sentences exceeded the cut-off and also 9 sentences from the correct condition were excluded despite being formally correct.

Hereafter, we ran a cloze probability (CP) test that allowed us to examine the prediction of context-specific words (Taylor, 1953) that in our case is considered as the target word (primary response) after the sentence fragment has been presented (Bloom & Fischler, 1980). 67 participants responded to an online form where they were asked to complete 186 sentences that were interrupted before the target word. We analyzed the completion and we assigned a CP value to the target words. 92 of the sentences obtained a CP value below 0.05 and these were considered to be "low CP" and the remaining items being considered as "medium-to-high CP" with a homogeneous distribution unbalanced toward low values (mean= 0.422). High cloze-probability sentences had therefore highly predictable target word whereas low cloze-probability sentences contained target words that are difficult to be predicted from the context (see Table 3.2).

CONDITION	**SENTENCES**
High cloze-probability, well-formed	Il meccanico ripara il <u>motore</u> del camion.
	[The mechanic repairs the <u>engine</u> of the truck]
Low cloze-probability, well formed	Il negozio vende <u>sciarpe</u> marroni.
	[The shop sells brown <u>scarfs</u>]

Table 1.2 - *The critical word for ERP averaging is underlined.*

3.2.2 – Apparatus

An HP PC (Model: Z220 Workstation) controlled the timing and the presentation of the stimuli while a Dell PC (Model: Precision 390) was dedicated to the recording of the EEG signal via BrainVision Recorder 2.0 (Brain Products GmbH). Stimuli were sent to a 22.5” monitor (VPixx Technologies Inc.) that was set to be at a refresh rate of 100 Hz with a resolution of 1900x1200. Importantly, we handled the latencies when the experiment was programmed which allowed us to have perfect synchronization between the onset of each word on the screen and the markers. The EEG experiment was programmed in E-Prime 2.0 (Psychology Software Tools). Data were preprocessed using BrainVision Analyzer 2.1 (Brain Products GmbH). To record EEG data, we used a set of different sizes of the Easy Cap 64 Ag/AgCl passive electrodes caps from Brain Products with the recommended conductor gel (Abralyt 2000). The entire EEG experiment was conducted in an electromagnetic shielded cabin with the function of a Faraday Cage. EEG exported data were analyzed with a MacBook Pro (Apple Inc.) using R Studio updated to the last version (October 2018). Behavioral tests were programmed, delivered and analyzed as shown in Table 3.3.

As reported in participants paragraph, 5 CI users had to be tested off-site (Milan) with some differences in the adopted apparatus. First, the EEG experiment was not conducted inside a Faraday cage and for this reason we adopted the same EEG caps (EasyCap, Brainproducts), but we used shielded amplifier to reduce ambient interferences. We also adopted two laptops to record the EEG signal and to provide participants with the stimuli (respectively, Dell Latitude and HP Pavilion). Both computers were loaded with the same version of the software and with the same executables that we used in the laboratory described above. The room where the experiment was similarly lit, and we removed most of the distractions by placing the stimuli laptop monitor against a blank wall.

TASK/FORM	SOFTWARE	DEVICE	SOFTWARE FOR ANALYSES
Sentence-Picture Match	Opensesame 3.2.5 [1]	Tablet HTC Nexus 9	R Studio/MS Excel
Verbal-Fluency Task	Matlab R2018a	MacBook Pro	R Studio/MS Excel
Grammaticality Judgement Task	Google Form	Tablet HTC Nexus 9	R Studio/MS Excel
Error-Detection Task	Print of MS Word	Paper & Pencil	R Studio/MS Excel
Lexical Decision Task	Opensesame 3.2.5 [1]	MacBook Pro	R Studio/MS Excel
Self-Evaluation Form	Google Form	Tablet HTC Nexus 9	R Studio/MS Excel
Anamnestic Form	Google Form	Tablet HTC Nexus 9	R Studio/MS Excel

Table 3.3 – *Behavioral tasks in the first column were consistently conducted between participants with the software (2nd column), the hardware/device (3rd column) and resulting data were organized and analyzed with the software in the 4th column.* [1] *(Mathôt, Schreij, & Theeuwes, 2012);* [2] *(Screen size: 15", resolution: 1440x900)*

3.2.3 – Procedure

Each participant was tested in a single session, lasting approximately 3 hours. After filling the informed consent and being prepared with the EEG cap, participants were asked to sit inside dimly lit cabin that served as a Faraday cage (with the exception of 5 CI users, as detailed above). During the preparation of the cap participants were provided with a tablet where the sentence-picture matching task

(SPM), the grammaticality judgement task (GAT) and the self-evaluation questionnaire (SET) were loaded. All these tasks were part of a set of behavioral measures that also comprises a semantic fluency task (SFT) and an error detection task (EDT) and a Lexical Decision task (Lex-Dec) that were run after the EEG session. A detailed description of these tests follows below. CI users received instructions at the beginning of the session before they were asked to remove their CI (or CIs) right before the preparation of the EEG cap. We provided oral instructions to participants that anticipated also the phase of the experiment in which they would have been unable hear. We further explained the EEG experiment by showing them examples from a computer in addition to the oral instructions. This allowed us to be sure that participants understood well the task. When ready, subjects were accompanied inside a dimmed light cabin where they sat on a comfortable chair in front of a screen (distance between the eyes and the monitor = 70 cm ± 5 cm). Subjects were provided with a standard keyboard with marked keys for answers.

The experimental session consisted in silently reading 320 sentences divided in four blocks on the computer monitor. Each block contained 80 randomized sentences with a fixed randomization across subjects. Additional twenty sentences were added at the beginning of the session as a practice. Participants were asked to carefully and silently read the sentences. Sentences were presented one word at a time for 300 ms followed by a blank screen (ISI = 300 ms; SOA = 600 ms) using a classic RSVP (Rapid Serial Visual Presentation) paradigm. The end of each sentence was marked with a full stop at the end of the last word to avoid any unnecessary expectation for another element to come. At the end of each sentence, they were asked to answer an acceptability question (“Do you think that the sentence was acceptable?”) by pressing “m”/ “c” on a keyboard for “yes” and “no” respectively and vice-versa depending on the counterbalanced randomization assigned to each participant (see Figure 3.0). Since a reading experiment with an end-of-sentence acceptability judgement task, is not always easy for participants to understand, we provided detailed instructions both written and oral well explaining what «acceptable» meant in our task. Specifically, “acceptable” can be translated into “a sentence that doesn’t sound bad and that is meaningful in the real world». This definition is valid for both semantic and syntactic violations and we also specified to participants that there would have been two types of violations by giving them some examples. Our aim was for the subjects to be able to judge whether the sentence was grammatical and semantically coherent. The acceptability question remained on the screen for 2 seconds; trials with missing acceptability answers were nonetheless considered in the EEG data analyses. Before the beginning of each sentence participants saw a fixation cross in the middle of the screen. The start of each sentence was triggered by the subject by pressing the spacebar on the keyboard providing them with time to blink between each stimulus. Participants were instructed to reduce at most movements of the body and of eyes and head primarily.

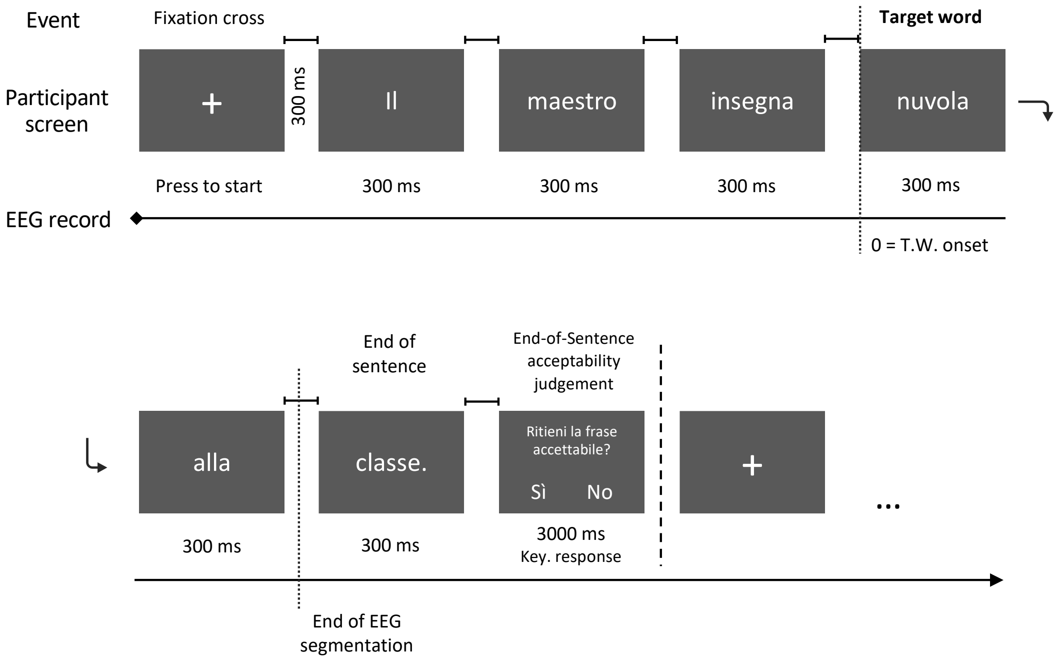

Figure 3.0 - *Visual representation of the employed EEG paradigm. Participants saw a fixation cross at the beginning of each trial. Only after they pressed the space bar, the sentence started to appear, one word at a time. At the end of each sentence participants were asked to answer a question that translated in English is "Do you think that the sentence was acceptable?". Subjects answered by pressing one of two buttons on a regular keyboard. The horizontal black line represents the EEG recording; the first dotted vertical line represents the marker at the beginning of the onset of the critical word; the second vertical dotted line stands for the end of the segmentation applied off-line during the preprocessing. The vertical dashed line represents the end of a trial (sentence).*

3.2.4 – EEG recording and data preprocessing

EEG signal was continuously recorded using 64 electrodes arranged according to the 10/10 system into an elastic cap (see Figure 3.0.2). Two mastoids channels (the left one used as the online reference) and one ocular channel for vertical eye movement were attached directly on the skin (not through the cap) in order to have a cleaner and more stable signal throughout the entire session. The ground was placed on the median line between channels FPz and Fz. Horizontal eye movements were monitored through electrodes F9 and F10, used as bipolar channels during offline preprocessing. The right and left mastoid channels were used to offline compute the average reference and their impedance has been kept below 5 KΩ. When possible, all other channels were adjusted to keep the impedance below 10 KΩ. In the rare cases in which this criterion was not achievable, we accepted values up to 15 KΩ. The signal was amplified using two Brain Amp DC amplifiers. The EEG signal was sampled at 1 kHz, with a band-pass filter from 10 to 250 Hz applied online, and then offline down-sampled at 200 Hz. Data were subsequently filtered with a low cut-off of 0.05 Hz and a high cut-off of 70 Hz both with a slope of 24 dB/oct. A notch filter at 50 Hz has been used for the 5 CI users (S1010, S1011, S1012, S1013, S1014) recorded outside of the Faraday cage. After the filters were applied, we segmented the EEG track around the target words from -400 to 1300 ms. In this stage we kept a slightly larger time window in order to be able to detect artifacts that otherwise would have been across the cuts and potentially ignored. Ocular artifacts were rejected by removing segments containing a maximum peak to peak amplitude that exceeded 200 µV on vertical and horizontal electrooculogram channels (VEOG; HEOG). The same automatic artifact rejection procedure was applied to all the remaining sites, with an allowed difference in the EEG values of 160 µV. A shorter segmentation was then applied from -300 to 1200. In each survived segment we corrected the baseline from -200 to the onset of the target word in order to counter long trends as well as any effect triggered by the previous word. Data were averaged for each condition (semantic correct, semantic violated divided in high and low cloze probability each; syntactic correct; syntactic violated) and again filtered with a high cut-off at 12 Hz with a slope of 24 dB/oct. Data were finally exported in BESA text format, to be manipulated and analyzed with R.

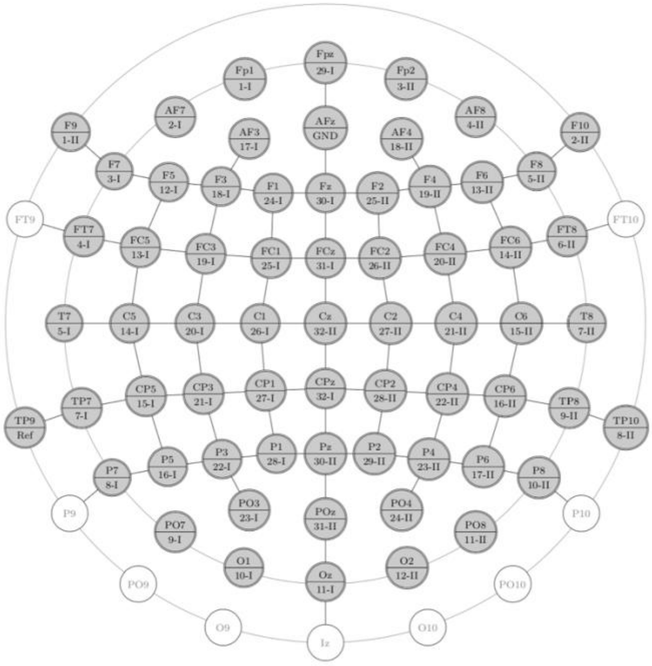

Figure 3.1 – *Schematic representation of the electrodes' distribution on the scalp. Given their importance (reference ch.), channels TP 9 and TP10 were detached from the cap and directly attached on the skin for a better signal stability throughout the entire experimental session.*

3.2.5 – Behavioral measures

We developed a battery of behavioral tasks to work alongside with the ERP experiment. We could gather the tasks in two main groups: one related to semantic and vocabulary knowledge (verbal fluency task and lexical decision tasks) and one focused on the grammatical and syntactic skills of participants (sentence-picture match task, grammaticality judgement and error detection tasks). Finally, we asked participants (or their parents when their assistance was required) a self-evaluation on several aspects of their speech, written, oral comprehension and grammatical confidence on their L1. All adopted tests are described in detail below and reported in full at the end of this thesis (see Appendices).

Lexical-decision task. For the lexical-decision task we built two lists of words and non-words, comprising 160 items each. For real words, we used the target word stimuli used in our ERP experiment. Non-words were created by replacing random letters (one or two) within the real words maintaining the items orthographically and phonologically legal for the Italian language (e.g. “ristorante” [word] turned into: “rispolante” [non-word]). We never changed the first or the last letter and we provided participants with the list with words that they did not see during the ERP experiment in order to avoid any memory effect. Participants sat in front of a laptop in a silent room with dimly lights. They were instructed both with oral and written information to press two specific buttons, one if the word was real, the other if they did not recognize the word. The order of the two buttons was randomized between participants and was assigned at the beginning of the session. With this task we aimed to either test the vocabulary knowledge of participants also collecting a discrete measure thanks to the reaction times and at the same time, we aimed to test whether the vocabulary level of the two list in the ERP experiment was balanced between the lists.

Semantic fluency task. The semantic fluency task was introduced to serve as proxy of lexical expertise and knowledge of subjects. In order to have a production test we asked people to pronounce all the nouns they can think about two different categories: fruits and animals. For each of the two categories, participants were instructed via oral and written information, to immediately start to talk as soon as the category name appeared on screen. They were automatically recorded for 30 seconds and they were then visually alerted when the time was over. Importantly, to avoid any effect of shyness as much as possible, we let participants alone in a dedicated room normally lit.

Grammatical Accuracy (GA) task. The aim of the grammatical accuracy task was to evaluate grammatical skills and knowledge of participants. We asked them to judge some sentences labeling them with “correct” or “wrong”. Half of the sentences contained an error, half of them were correct. We built 80 sentences manipulating the class of the verb (transitive, unaccusative and copula) and the type of the subject (morphological, syntactic and complex) with the subject being also either singular or plural (note that when syntactic, the subject could only be plural). Transitive verbs expect an object after the verb; in sentences with unaccusative verbs, the subject shared the characteristic of the object and copula is a word used to bind the subject with a predicate. Morphological subject was characterized to be identifiable for number and gender; complex subject was composed by a subject and a complement (e.g. The dog of Jack […]) and the syntactic type of subject consisted of two subjects explicitly expressed (e.g. Jack and the dog […]). All these combinations of manipulations have been randomized and were presented to participants half in the correct and half in the violated condition with violations being embedded in the aforementioned manner.

Error detection (ED) task. The error-detection task was conceived as a way to probe orthographic and grammatical abilities of participants, and it has been built by creating a text that contained errors of three different kinds: orthographical, syntactic and morpho-syntactic, each type repeated six times. This task allowed us to introduce different kind of errors in a written form that was more naturalistic by being a text with sentences that are context-coherent. Hence, we developed a meaningful text with embedded phonological, syntactic and morph-syntactic mistakes. Each error was inserted in a different phrase within the text with no sentence containing more than one violation. We asked participant to find as many errors as they can in an unlimited amount of time. The score was arbitrarily assessed with 1 point for each correct identification of the error (maximum = 18).

Sentence-picture matching (SPM) task. The sentence-picture matching task comprised 6 different categories of sentences, with an increasing syntactic difficulty rate. It was conceived to probe semantic, lexical and syntactic expertise of participants. Subjects were instructed to assign one out of four different illustrations to a sentence presented in the middle of the screen. The pictures were built so that one 1) was the target picture, 2) one is a distractor with the correct action (verb) but the wrong characters (subjects), 3) one is a distractor opposite from the previous one and the last 4) being a pure distractor with both wrong action and characters. Illustrations were extracted from the Comprendo Test (Cecchetto, Di Domenico, Gaffarra, & Papagno, 2012) and arranged according to our sentences and combinatory requirements. Knowing a grammatical rule, does not guarantee that people are also capable to understand the content of a sentence. This means that we can find people with a perfect grammar knowledge and a good skill in identifying syntactic violations without understanding the content of the sentence.

Sentences were adapted from materials available in the Comprendo battery (Cecchetto et al., 2012) This battery is validated for adults (age > 20) and it is not specifically assessed for hearing-impaired people. Because this test was not meant to answer specific questions of our interest, we decided to extract and adapt some of the type of sentences of the test and to apply specific manipulations.

1- **Transitive sentences.** These sentences are meant to be our baseline level of complexity for two main reasons: they have a simple syntactic structure with a subject followed by a transitive verb followed by an object. From a semantic perspective, they all reflect simple situations (e.g. “The dog chases the cat”). Noteworthy, for many of these sentences, the target picture was also a very common situation like in the example above. It is frequently indeed, to find the cliché of a dog chasing a cat rather than the opposite in the common knowledge, especially in children literature. To avoid false positive data with participants that didn’t understand the sentence, but that hit the target picture just because it was the most obvious one from a semantic point of view, we also presented a variation where the object became the subject and vice versa (for example: *“The dog chases the cat”* turned into *“The cat chases the dog”*).
2- **Dative sentences.** These sentences should have had a structure with the subject in the first position, followed by a dative verb such as *“to give”* and the complement occupying the last position (e.g. *“The mother gives the cake to the grandmother”*). The potential problem with these sentences is that they can be understood just by reading only the content words: <mother gives cake grandmother> ignoring function words and free morphemes. Since we know from the literature on deafness that deaf people tend to focus more on content words, we wanted to avoid the

possibility to encounter false positive responses. Therefore, we modified the sentences creating a clitic-sentence minimum-couple (e.g. *"Le dà la nonna"* [PRO$_{+pl+object}$ gives the grandmother $_{+subject}$] – *"Le dà alla nonna"* [PRO$_{+pl+object}$ gives to the grandmother]). In this case, the absence or the presence of the preposition is crucial: the presence of the "It" (2nd sentence) correlates with a null subject whereas the absence of the preposition (1st sentence) correlates with a postverbal subject. By removing parts within a sentence, we set a challenge for deaf CI users since we know that this population has trouble to manage clitics and syntactic complex sentences. We divided the two set of sentences in two categories following the example above expecting an overall worse performance in both structure for CI users compared to controls and in particular we expect a drastic drop in the performances for CI users in the category that contain sentences without the dative preposition.

3- **Passive sentences.** Passive sentences have been divided in two subcategories: one with an explicit agent (e.g. "The dog is watched by the man"; and one where we removed the agent (e.g. "The cat is watched"). In these two groups of sentences we operated a complexity manipulation by removing one element from the sentence. The removed element was not fundamental for the identification of the correct image, but that was helpful to discard distractors.

3.2.6.1 – Self-Evaluation Form

With the Self-Evaluation Form, we aimed to obtain a self-assessment of the linguistic skills and abilities of the subjects. We asked them to autonomously answer a set of questions in a Google Form questionnaire. The form was built to be sensitive to four subdomains of human language: reading, writing, speaking and listening.

4.0 – Written sentence processing in a wide age-range spectrum of normal hearing participants

4.1 – Preface

The main aim of the project was to better understand the mechanisms behind the acquisition and the development of language in deaf people with cochlear implant as it has been shown in the previous two studies. In order to have a control population for the two CI groups, we also collected data from normal hearing people and because we knew that the collection of this group would have been faster than the clinical one, we recruited many participants in a wide age range to later match them with the group of CI users. This resulted in a rather large group of participants that covers an age range from twelve years up to 70 years (more details follow in the methods section below). By having a group so well distributed along the age-spectrum of life, allowed us to treat this group not exclusively as a container from which to extract subjects in order to match CI users for age. Instead, this group was perfect to serve the aim of collecting normative data on the ERP correlates of semantic and syntactic subject-verb number agreement violations in Italian as a reference benchmark to study specific populations such as bilinguals, subjects with atypical language development and people with language disorders at different ages.

This study of age effects on classic ERP pattern elicited by syntactic violations is less studied if compared to the age effect on the N400. Possible age variability of LAN+P600 could be informative with respect to the wide debate on variability across structures, languages and individuals of ERP correlates of syntactic violation (see for example Molinaro et al., 2015; Molinaro, Barber, et al., 2011; Tanner, 2014; Tanner &

Van Hell, 2014 for the debate on the biphasic pattern LAN + P600). With this dataset we hope to bring a new contribution that can help to disentangle some aspects of the debates such as the existence of the LAN and the variability in topography and amplitude of N400, LPC and P600. Even just at a qualitative level, we have seen potential differences between the NH control group of the first study compared to the subsample selected for the second study (i.e. N400 as a function of the cloze probability) proving the value of this large group of participants. As previously stated, we hope with this study to lay the groundwork for future investigations on the nature and the sources of variability of ERP effects with particular attention to age effects.

4.2 – Introduction

To date, the N400 and the P600 are considered to be well established and fixed components for the L1 in monolinguals. However, there are works in the literature that seem to challenge this idea of the functional interpretation of the N400 and the P600 (but components in general) to have a monolithic functional interpretation between subjects. In recent years, an increasing number of studies (e.g. Tanner & Van Hell, 2014) focused the attention at individual variability that for years has been neglected. Language processing should be considered as a dynamic system rather than fixed. Therefore, according to this perspective, N400 and P600 could not be directly linked to the linguistic phenomenon. The scientific community should start considering that between components and the neural substratum there is a cognitive layer that could be different across individuals and/or aging. With a subject-verb number agreement violation, we usually expect to find a P600. Although the majority of studies agree with this statement, some studies did actually find ambiguous results. Moreover, with respect to the preceding negativity the subject-verb dependency has shown, throughout the literature, a huge variability across languages, laboratories and tasks. For example, Tanner (Tanner & Van Hell, 2014) found for the aforementioned violations, both the P600 in the majority of the cases but, in a few subjects, also an N400 in response to syntactic-agreement violation. In their study, forty English participants were instructed to silently read a set of sentences in a classic RSVP paradigm with an acceptability judgement at the end of each sentence. Although the average analysis of the waveform showed the classic LAN + P600 biphasic pattern, at single subject level they found a continuum between a negativity and a positivity activation across subjects with some of them showing the classic P600 (positive responders) while others were showing an N400-like activation instead (negative responders). This negative response that is usually associated with semantic violations is also elicited by syntactic violations in English L2 learners (English as second language). As a result, Tanner and collaborators hypothesized that the biphasic pattern LAN + P600 is not an actual biphasic pattern. Instead, they suggest that the presence of the negativity and the positivity is the result of the overlap of an N400 of some subjects with the P600 of the others in the process of averaging (Tanner & Van Hell, 2014, McKnight et al., 2018). They call them respectively negative and positive responders depending on their activations during the experiment and the core interpretation that they give is that it depends on the handedness. Being left-handed or even just having a left-handed relative should result in a different pattern of activations in result of a syntactic agreement violation (Tanner, 2014; Tanner & Van Hell, 2014). On the other hand, other researchers proved the biphasic pattern LAN+P600 to be reliably present both at items and individual level. One study in particular specifically tested this hypothesis by asking eighteen Spanish speakers to read 240 sentences presented word by word on a monitor. Half of the sentences contained article-noun gender agreement violations and the other half served as a control condition. As already anticipated, they found that local agreement violations elicit a biphasic pattern LAN + P600 even when linear-mixed models were run after accounting for individual variability. The authors disconfirmed previous results that challenged the existence of the left-anterior negativity showing that a biphasic pattern composed by a LAN followed by a P600 can be reliably linked to morphosyntactic violation (Caffarra, Mendoza, & Davidson, 2017). However, it is important to highlight that the language (English vs Spanish) and the structure tested (subject verb agreement is a long distance across phrase dependency while determiner-noun violation is a more local one) may explain the differences between Tanner and Caffarra studies. Moreover, Tanner's study possibly could not have enough item for each subject to clearly measure subject-level responses with a good signal to noise. The only link between positive/negative responders and cognitive individual differences that Tanner et al (2017) found is handedness (familiarity) and this does not allow to clearly understand what the positive or negative responses correspond to in terms of cognitive processes during sentence comprehension (Grey, Tanner, & van Hell, 2017). Despite all these limitations Tanner et al. (2017) proposal clearly signals that individual variability of ERP responses to a same violation within a population of native speakers may exist and Caffarra et al. (2017) show that these possible differences could have differentially impact ERPs correlates of syntactic violations across languages and/or dependency. In this study we collect ERP responses to subject-verb violations in Italian, a dependency for which across-studies variability is documented in the literature (Kasparian et al., 2017).

To better understand the individual variabilities among a group of Italian native speakers, we collected ERP responses to subject-verb violations. We used the same set of stimuli and paradigm described in the first study on preverbal CI users (see Chapter 3). In fact, data from hearing participants from study 1 and study 2, is a subsample extracted from the group described in this study. To summarize, we presented 320 sentences divided in 2 sets: eighty (80) sentences were semantically violated, 80 had a syntactic violation embedded. 160 sentences (80 per condition) were used as control fillers. Participants were required to silently and carefully read the sentences and to perform an acceptability judgement at the end of each sentence with the press of a button. We divided participants in 4 age groups that were unbalanced having longer age ranges with the increase of the age (further details in the methods paragraph).

4.2.1 – The N400 and the P600, studies on aging

N400 and P600 have already been studied in relation to ageing effects. If we consider the syntactic condition alone, although we have seen that the debate is still open, we did not expect to find any difference between age-groups. De-facto, even for the younger group that went from 12 to 17 years, we did not expect any particular difference in the components since it has been proven that in Italian, complex syntactic structures such as object relative clauses that are disambiguated by number are acquired at the age of 12 years (De Vincenzi et al., 2003). Despite the widespread assumption that grammatical competence and performances in processing morphosyntactic aspects of language are rather stable from puberty to elderly, a recent study suggests that grammatical diversity can show non-linear changes in adulthood.

In a recent study in English it has been investigated the effect of aging by analyzing dyadic conversations and in particular, how several aspects of language changes through time and between sex. The researcher found that there are differences for sex with women showing a richer syntactic structure and a non-deterioration of their fluency. On the other hand, starting from the from the age of 45 onward, men exhibit a decrease in the diversity of the employed syntactic structures, also associated with speech disfluencies that increase overtime (Moscoso del Prado Martín, 2017).

Kutas and Iragui (1998) run an experiment specifically tuned to test the effect of age on the N400 component starting with the intent of investigating the semantic memory through time. They recorded EEG signal from the scalp through thirteen electrodes during a semantic categorization task of 72 adults ranging between 20 and 80 years old divided in 6 homogeneous age groups. Participants listened to sentences that were missing the last word and after one second, they saw on a screen a word that were coherent or non-coherent with the incomplete sentence that they hear right before. At the end of each sentence, they were required to provide an end-of-sentence acceptability judgement. Results showed that although all groups showed the N400 effect in response to semantic incongruities, with the increase of age, the component was smaller and with a delayed peak (Kutas & Iragui, 1998). They interpreted the smaller amplitude in older participants with the ease of integration and comprehension given by the richer semantic memory. The increase in latency was explained as a result of the increased number of connections that would have slowed down the onset of the post-synaptic potential recorded via EEG. An alternative interpretation that they provided was more simply related to a generic decline of the speed of processing. Another experiment that aimed to investigate the effect of age on the linguistic components was carried some years before the one mentioned above. In this case also, researchers found similar results with a decrease of the peak amplitude and a longer latency (Holcomb, Coffey, & Neville, 1992). Other studies with the same paradigm in the literature found differences in the late-positive component (LPC) when compared participants from 5 to 11 years old and another group that ranged from 20 to 33 years with the LPC that was found only in the oldest group (Juottonen, Revonsuo, & Lang, 1996). Lastly, in 2005, Kutas and Federmeyer tested young participants (between 18 to 24 years) and compared them with a group of older subjects (60-76 years old) using EEG. They used a reading task in which the last word was always coherent with the sentence, but it was modulated in its cloze-probability (high vs. low). They found that the N400 in low cloze probability conditions was larger for both groups, but the difference between conditions was significantly smaller in the older group (Federmeier & Kutas, 2005). In summary, to date, the picture around the evolution of the N400 with the increase of age is rather clear: longer latency and weaker amplitude at higher ages.

There is more uncertainty around the P600 when we consider that it has been tested in a very small number of studies. Moreover, the existing literature that covers the topic, only compared small age ranges. Young participants from eight to thirteen and an adult group ranging from eighteen to twenty-seven years old were tested by Atchley et al. (2006). They used fifty acoustically delivered interrogative sentences, where the syntactic violation could have been the omission of the verb or a number-agreement syntactic violation. The P600 elicited by the omission of the verb didn’t show any statistical difference but the agreement violation elicited, in young participants was slightly longer and greater (Atchley et al., 2006). Another study investigated the P600 in a group of children from 7 to 13 years old divided in age-groups. In respect to the P600, it was elicited in all of the groups, from 7 up to 13 years of age (Hahne, Eckstein, & Friederici, 2004). Overall, they found differences only in the early LAN (ELAN) with the absence of this component in children from 7 to 10 years old. This experiment does actually provide a very small contribution in respect to our experiment given that the two samples are barely overlapping: 7 to 10 years old in the study from Hahne et al. (2004); 12 to 70 in our study. More overlapping ages can be found in another work in the literature that aimed to investigate the effect of age on the P600 only (Atchley et al., 2006 also contained a semantic condition). Kemmer and colleagues (2004) tested two groups of subjects: one composed by people from 18 to 24 years (mean age = 20 y.o.) and the other with participants ranging from 60 to 80 years old (mean age = 69 y.o.). Participants were asked to read three-hundred sentences on a computer monitor and to answer an acceptability judgement at the end of the sentences. Sentences contained a number-agreement syntactic violation that could be between the subject and the verb (as in our study) or in pronouns. Neither the amplitude not the latency was significantly different between the two groups. However, the distribution of the P600 changed, with younger participants showing a slightly left-lateralized central-posterior distribution while the older group was showing a more frontal-left/right symmetrical distribution (Kemmer, Coulson, De Ochoa, & Kutas, 2004).

4.2.2 – Our study

The group of hearing participants was collected with the primary purpose to be the control population for CI users acting as a benchmark to study the special population. As such, we expected to find the N400 in response to semantic violations and a biphasic pattern of LAN + P600 after the syntactic agreement violation. This homogeneous result would have served as the confirmation that our paradigm and stimuli were working properly replicating results in the literature in normal-developed population.

Some of the points of strength are shared with the other two experiments (Chapters 5 and 6) presented below. We still have a large number of items per condition, we still are recording from the same EEG system with an array of 64 channels and we are still testing the same well-established ERP components. Furthermore, we also are among the very few studies of language-related ERPs that took into consideration such a wide range of ages and to our knowledge, we are the first to test it in the Italian language.

4.3 - Methods, procedure and apparatus

Procedures, apparatus and the overall procedure follow the structure described in Chapter 3. Should any dissimilarity occur, it will be specified and explained.

4.3.1 – Participants

We collected data from 48 normal hearing and normal-developing participants. They were all tested with the same set-up in the same laboratory, following the procedure described in the methods chapter. Control participant from the two studies on patients were a subsample from this group. In this rather wide range of ages of participants resides one of the strengths of this study. We do not only have typical data from the university population which is usually over-represented in the vast majority of the studies, where age is not a concern. We also have data from that specific group, but it only is represented in one of the subsamples (Group 2), where ages were between eighteen and twenty-eight years. We divided participants in 4 age ranges as explained in Table 4.1. The decision to create uneven groups for age was taken because we assumed that it was more likely to find more potential differences between very young participants (group 1) and young adults represented by group two rather than from a hypothetical group from forty to fifty with a group from fifty to sixty given that all neural developmental processes do not changes significantly in the adulthood after twenty-five / thirty–five years old. Participants were all recruited through local recruitment system and through word of mouth.

GROUP	AGE RANGE	N	SEX	MEAN AGE (SD)
1	12-17	12	4M; 8F	15,5 (1,98)
2	18-28	12	3M; 9F	23 (3,16)
3	29-44	12	4M; 8F	37 (4,92)
4	45-65	12	5M; 7F	57,5 (4,91)

Table 4.1 - *Descriptive table of participants collected for this study.*

4.3.2 – Apparatus and procedures

We used the same apparatus and we employed the same procedure described in the methods chapter. The anamnestic questionnaire was limited to sections that were not addressing deafness-related items. None of the subjects of this study were tested at a different location as they have been all recruited locally. Should any difference occur, it will be thoroughly described.

4.4 – Results

4.4.1 - Behavioral results

End-of-sentence acceptability judgement – We calculated the d-prime index as described in the first study. The analysis revealed no differences between groups in the semantic condition whereas in the syntactic condition, a significative result emerged (Kursal-Wallis, $p = 0.035$) revealing a shift in the d-prime index with an overall better performance of the older groups compared to younger groups (group 1, in particular) (see Figure 4.0).

This difference in the semantic condition can be explained by assuming that the violations in the semantic set of sentences were more easily perceived by people with more years of language exposure. Standalone sentences, especially in the semantic condition, required more experience because they are decontextualized and, in some cases, despite explained during the preparation, violated sentences could have been interpreted as acceptable because of the inexperience of the youngest subjects. Overall though, in both conditions (semantic and syntactic), performances are rather aligned, and they did not reveal any unexpected result.

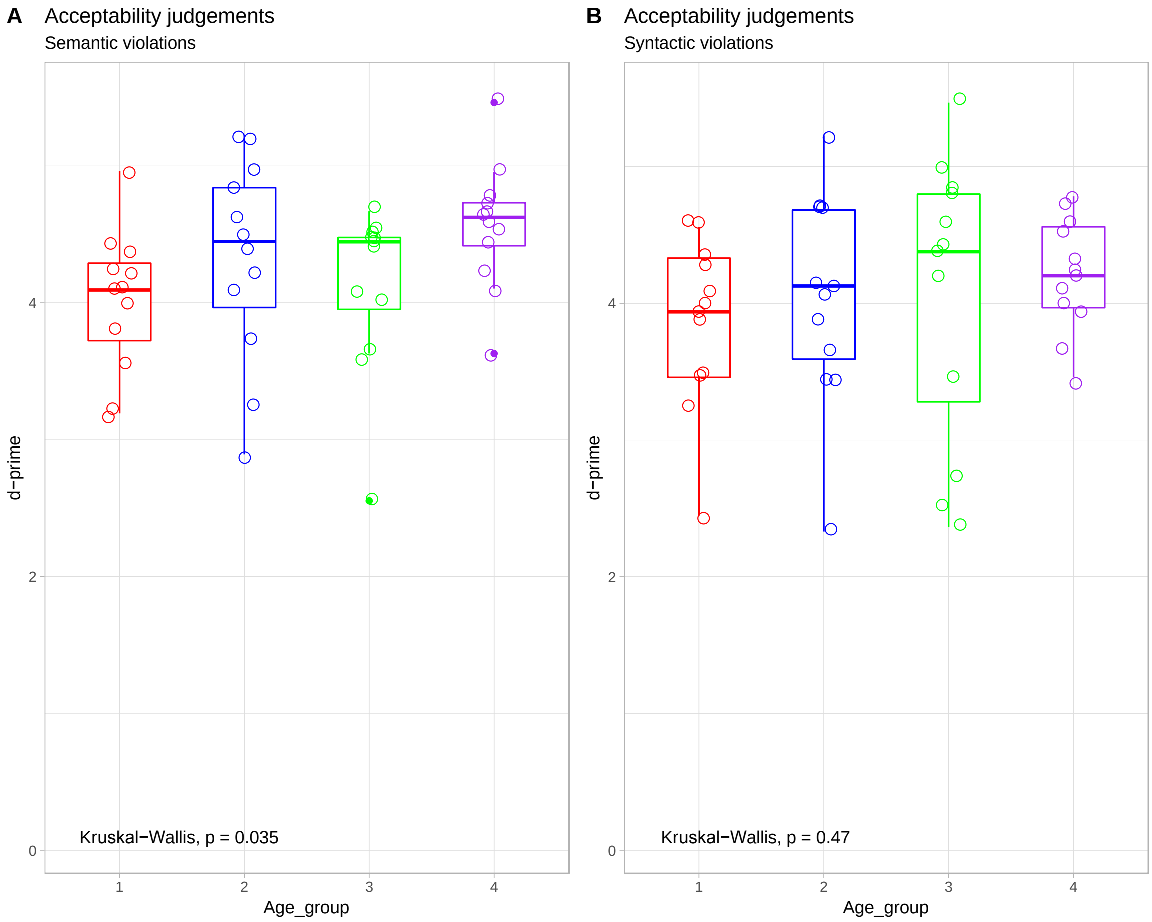

Figure 4.0 – *D-prime index (y-axis) across the 4 age groups (x-axis). Group 1 ranged from 12 to 17 years old (in red); group 2 from 18 to 28 (in blue); group 3 from 29 to 44 (in green) and finally group 4 ages ranged from 45 to 65 years old (in purple).*

4.5 – ERP results – P600

Results (Figures 4.1; 4.2; 4.3; 4.4) show that the posterior and late stage of the P600 is rather similar across the age groups after 18 years of age while different topographic distribution of the preceding negativities are present across the four age groups. On top of this, a large difference in the topography of the early stage of the P600 is present in the interval 550-650ms after word onset in that younger subject do show a posterior focus of the component while older groups also show the presence of a large positive deflection for the violation at more frontal sites. With respect to the nature of this effect, it should be noted that the age-difference mainly emerges in term of a larger frontal negativity for older subjects in the correct condition rather than as an augmented positivity for the violation. These age-related variations of the ERP response to a well-controlled syntactic violation in native speakers are interpreted by assuming that a same linguistic computation may be performed in different ways by individuals with different cognitive resources, depending on age. Moreover, we think that the interpretation of ERP responses to syntactic violation is far more complex than a specific pattern (LAN+600) or than a unidimensional continuum between negative responders (N400) and positive responders (P600) and that this interpretation should not only consider variability of effects (subtracted waveforms) but also the variability in the ERP responses to correct conditions only.

Group 1

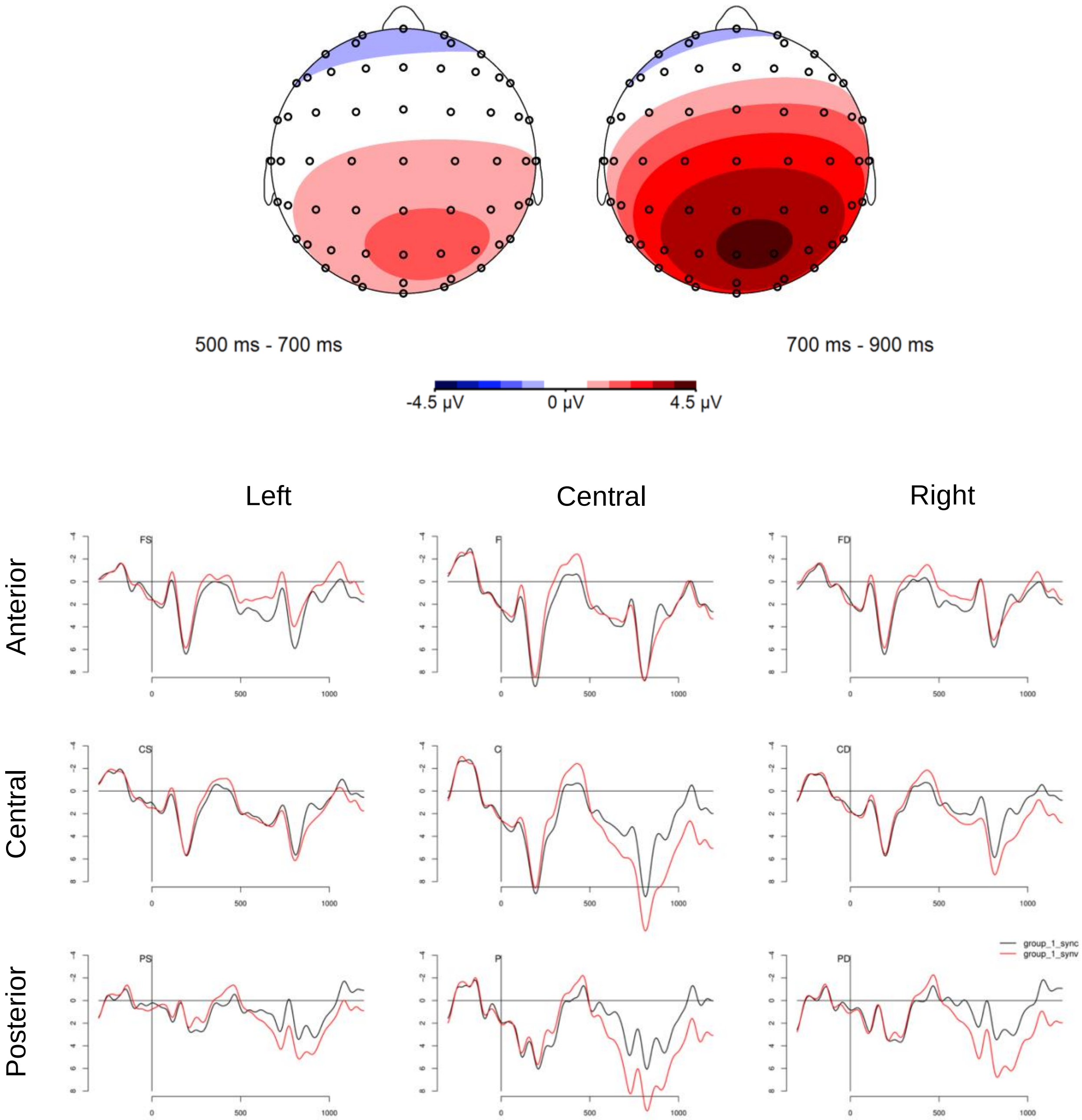

Figure 4.1 – ***A****) Averaged topographic distribution of the P600 between 500 – 700 & 700 – 900 ms after the onset of the target word for group 1 (N=12; 12 – 17 years old). The scale ranges symmetrically from -4.5 to 4.5 µV.* ***B****) Grand-average of waveforms in the 9 clusters of electrodes (FL frontal left, F frontal midline, FR frontal right, CL central left, C central midline, CR central right, PL posterior left, P posterior midline, PR posterior right) for the syntactic condition. Correct condition is represented in black; violated condition is represented in red.*

Group 2

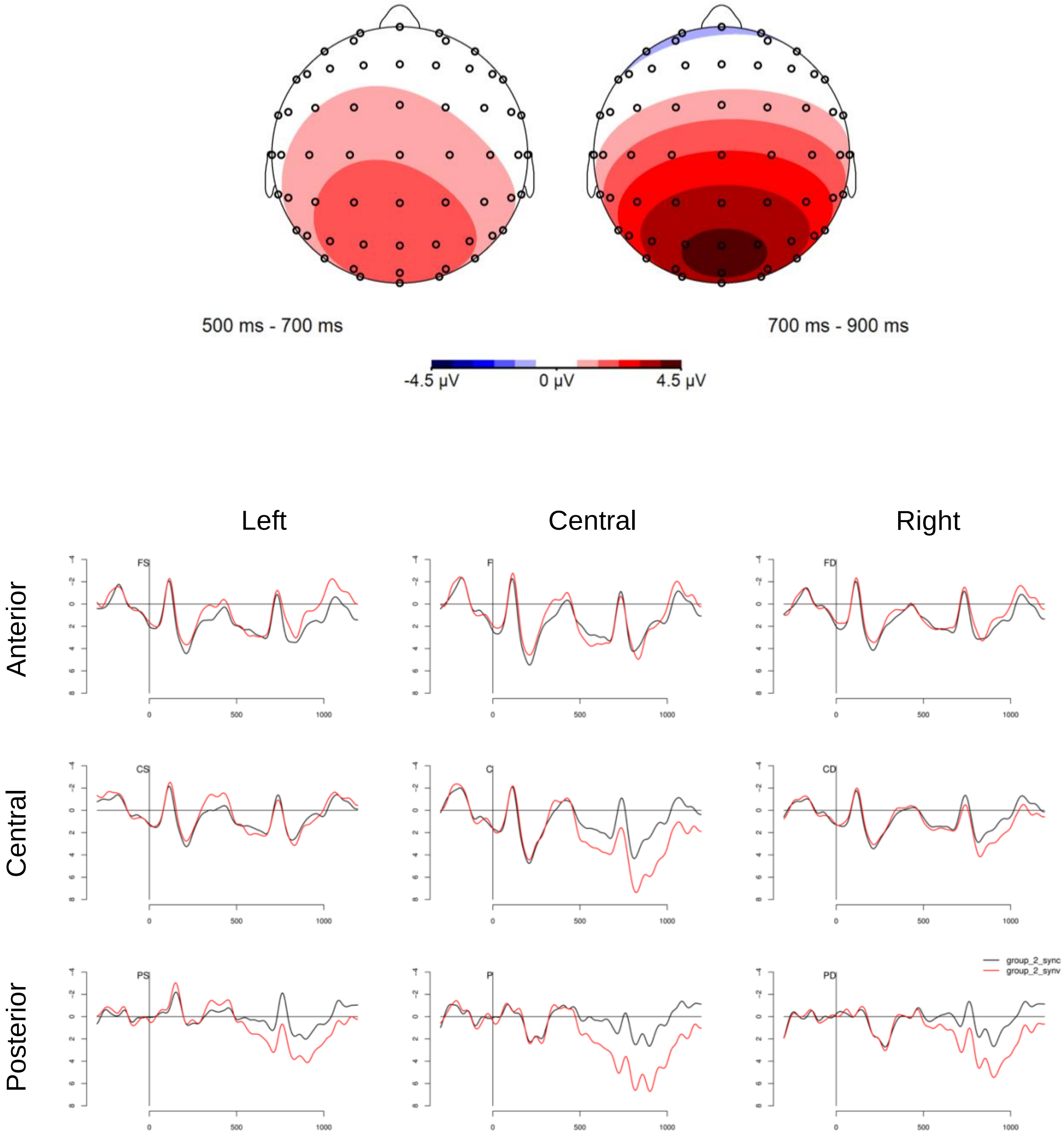

Figure 4.2 – ***A***) *Averaged topographic distribution of the P600 between 500 – 700 & 700 – 900 ms after the onset of the target word for group 2 (N=12; 18 – 28 years old). The scale ranges symmetrically from -4.5 to 4.5 µV.* ***B***) *Grand-average of waveforms in the 9 clusters of electrodes (FL frontal left, F frontal midline, FR frontal right, CL central left, C central midline, CR central right, PL posterior left, P posterior midline, PR posterior right) for the syntactic condition. Correct condition is represented in black; violated condition is represented in red.*

Group 3

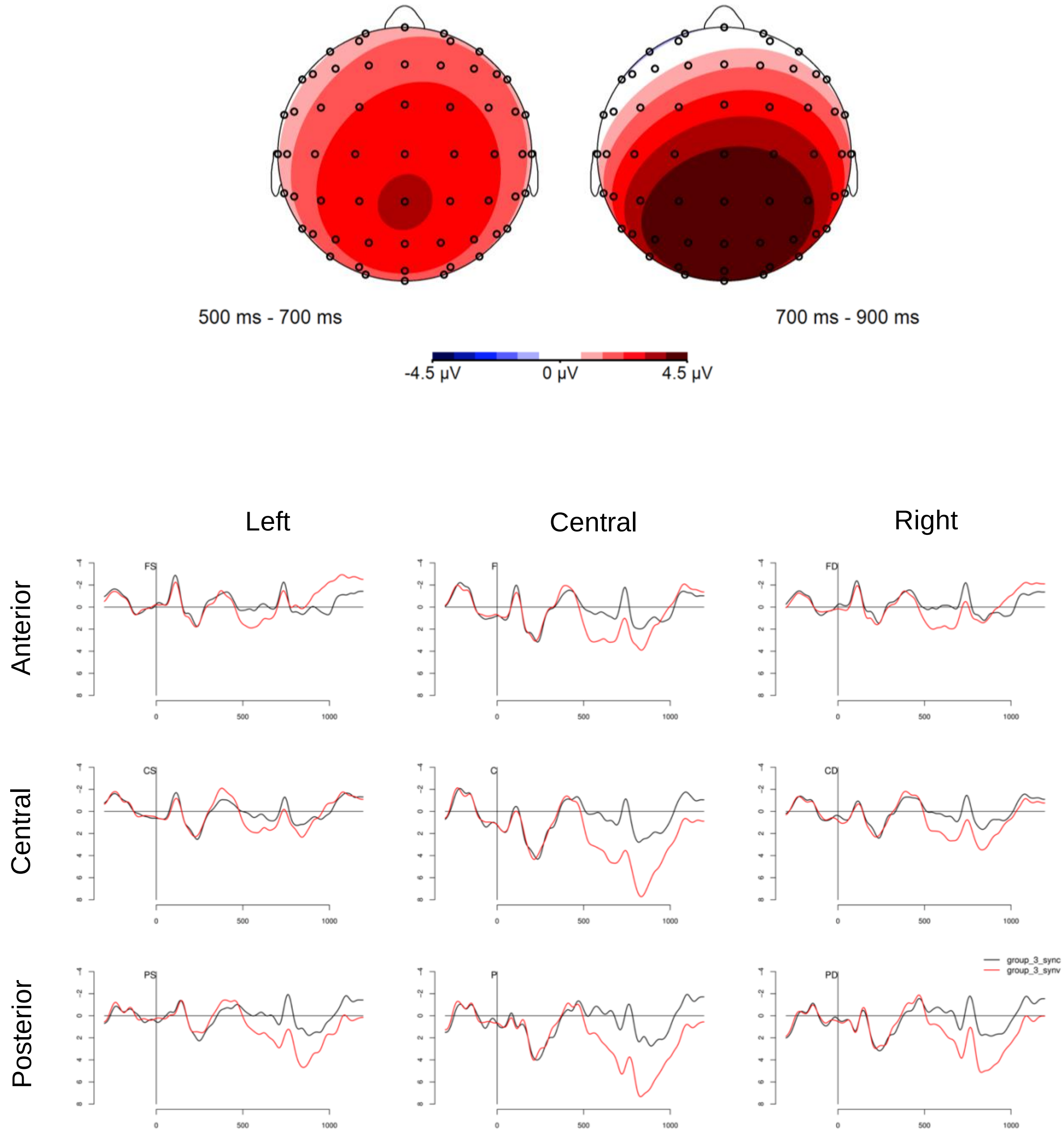

Figure 4.3 – ***A****) Averaged topographic distribution of the P600 between 500 – 700 & 700 – 900 ms after the onset of the target word for group 3 (N=12; 29 – 44 years old). The scale ranges symmetrically from -4.5 to 4.5 µV.* ***B****) Grand-average of waveforms in the 9 clusters of electrodes (FL frontal left, F frontal midline, FR frontal right, CL central left, C central midline, CR central right, PL posterior left, P posterior midline, PR posterior right) for the syntactic condition. Correct condition is represented in black; violated condition is represented in red.*

Group 4

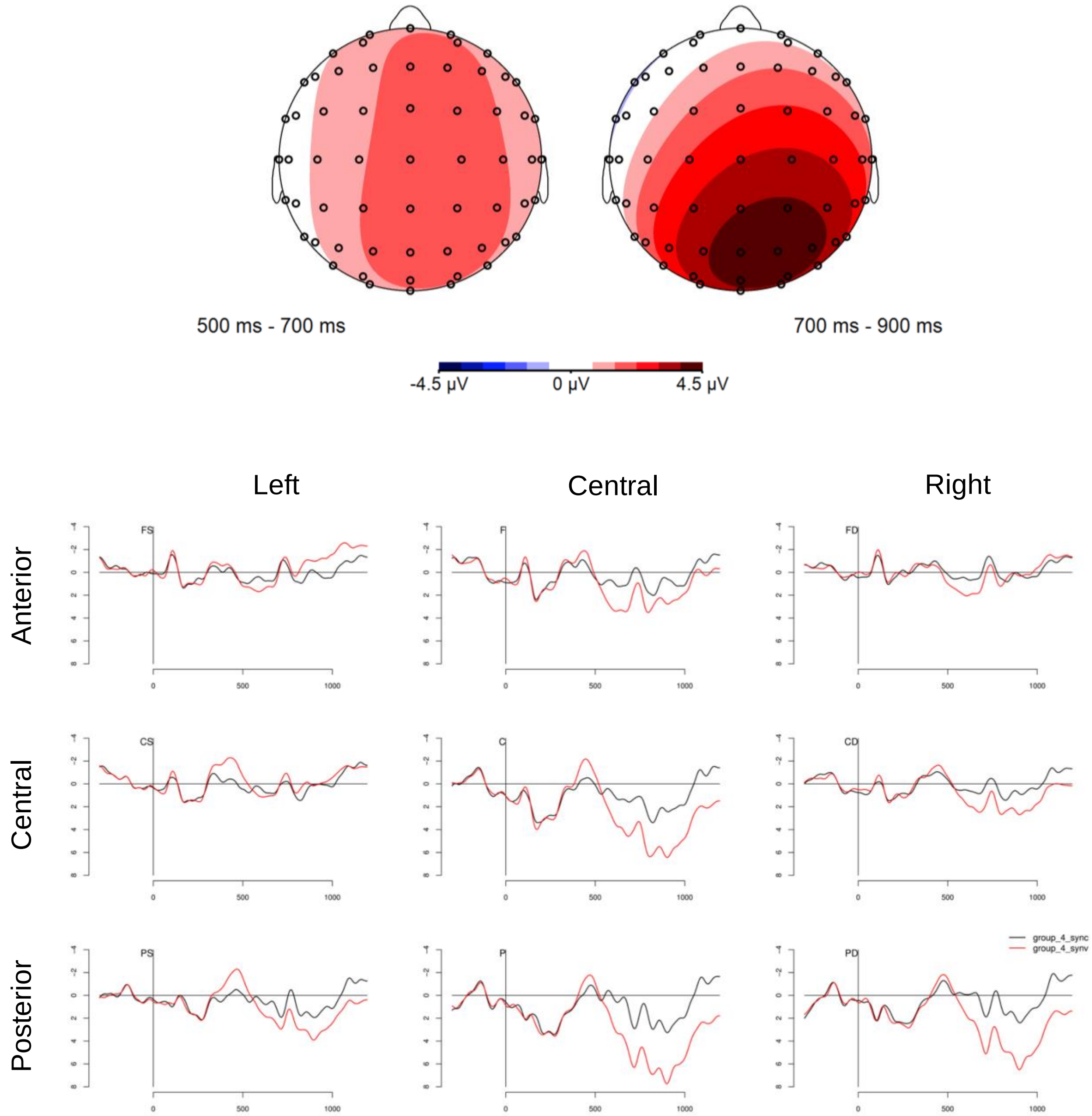

Figure 4.4 – ***A****) Averaged topographic distribution of the P600 between 500 – 700 & 700 – 900 ms after the onset of the target word for group 4 (N=12; 45 – 65 years old). The scale ranges symmetrically from -4.5 to 4.5 µV.* ***B****) Grand-average of waveforms in the 9 clusters of electrodes (FL frontal left, F frontal midline, FR frontal right, CL central left, C central midline, CR central right, PL posterior left, P posterior midline, PR posterior right) for the syntactic condition. Correct condition is represented in black; violated condition is represented in red.*

4.5.1 – LAN + P600, Visual inspection

Visual inspection on the entire P600 time window (from 550 to 1050 ms) suggests that the effect is present across all of the age groups, with a typical posterior distribution along the central line and in central-posterior sites. Still, P600 effects are visible also at lateral sites with smaller or absent amplitudes.

Interestingly, the early stage of the P600 seems more broadly distributed also on frontal sites in older groups whereas in the first group of young individuals is almost absent. The difference in the older groups emerge more in terms of a negativity of the control condition rather than a larger positivity of the violation. On the other hand, the later stage of the P600 seems to be comparable across age groups with a central-posterior distribution, especially along the midline.

We also visually inspected the time window of the LAN (300-500 ms) in both the midline but especially in the lateral clusters. In response to violations, we see small negative deflections with different topographies across the four groups of age. In group1 the deflection is limited to midline central-frontal clusters, possibly compatible with a rather frontal N400. In group 2, the negativity is left lateralized, evident in frontal and central left cluster (a topography compatible with the typical LAN). In group 3 and 4 the small left lateralized negativity seems larger on central and posterior left clusters and almost absent on the frontal left cluster (a topography likely to be classified as a left temporal negativity (LTN) (Osterhout & Holcomb, 1992). In group 4 the negativity extends to midline sites in which the N400 is typically present.

4.5.2 – LAN + Statistical analyses

We used a repeated measures ANOVA to investigate effects on the P600 along the central line in a time window from 550 and 1050 ms. The analysis revealed a main effect of GROUP ($F(3, 44) = 3.29$, $p = .029$, $\eta_p^2 = .18$); a main effect of CORRECTNESS ($F(1, 44) = 62.24$, $p < .001$, $\eta_p^2 = .59$); a main effect of LONGITUDE ($F(1.19, 52.52) = 20.87$, $p < .001$, $\eta_p^2 = .32$) and finally an interaction between CORRECTNESS and LONGITUDE ($F(1.22, 53.62) = 38.34$, $p < .001$, $\eta_p^2 = .47$). After visual inspection, the classic posterior P600 (where the channel "Pz" is located) seems to be consistent across groups whereas more differences appeared in the frontal sites with younger groups showing less frontal P600 effect.

The analysis of the left anterior negativity (LAN) has been computed on both the left and the right lateral lines (see paragraph 3.3.4) in a time window between 300 and 500 ms. A repeated measures ANOVA with CORRECTNESS (correct or violated), LONGITUDE (frontal, central and posterior) and LATERALIZATION (left, right) as within-participants variables, and GROUP as between-participant variable was run to test whether the LAN has been reliably detected and whether it was changing over the lifespan. The ANOVA revealed two interactions: one between CORRECTNESS and LATERALIZATION ($F(1, 44) = 4.98$, $p = .031$, $\eta_p^2 = .10$) and one between LONGITUDE and LATERALIZATION ($F(1.33, 58.55) = 3.85$, $p = .043$, $\eta_p^2 = .08$), but no interaction with the between-factor GROUP. Despite the large variation in topography of the early negativity across the four age groups that we described in the visual inspection, the only significant interaction is between correctness and lateralization suggesting that overall, this negativity tends to be left lateralized. The fine-grained variations in topography across groups that should have emerged in terms of higher order interactions with

GROUP and topographic factors resulted thus not to be significant with this scheme of analyses.

4.5.3 – early/Late P600

We divided the time window of the P600 in two sections with the first being between 500 and 700 ms. The ANOVA on the early part of the P600 revealed two main effects: one for CORRECTNESS (F(1, 44) = 36.32, p < .001, η_p^2 = .45) and one for LONGITUDE (F(1.18, 52.00) = 16.79, p < .001, η_p^2 = .28). Moreover, the interaction between these two variables resulted to be statistically significant (F(1.21, 53.24) = 6.11, p = .012, η_p^2 = .12) indicating that the effect (across groups) is larger on posterior sites. Differently from what we expected based on visual inspection which suggested a topographic variability across groups of the early P600, no interaction of CORRECTNESS with GROUP and LONGITUDE was found.

The second stage of the P600 was investigated between 700 and 900 ms with the same methodology employed in the previous paragraph. Accordingly with the results on the early stage of the P600, we found a main effect of CORRECTNESS (F(1, 44) = 59.14, p < .001, η_p^2 = .57), LONGITUDE (F(1.22, 53.83) = 31.25, p < .001, η_p^2 = .42) as well as the interaction between the two (F(1.29, 56.57) = 42.10, p < .001, η_p^2 = .49). Interestingly, we also found a robust main effect of GROUP (F(3, 44) = 5.39, p = .003, η_p^2 = .27) which indicates that there could be a difference between groups in both correct and violated sentences.

4.6 – ERP results – N400

Group 1

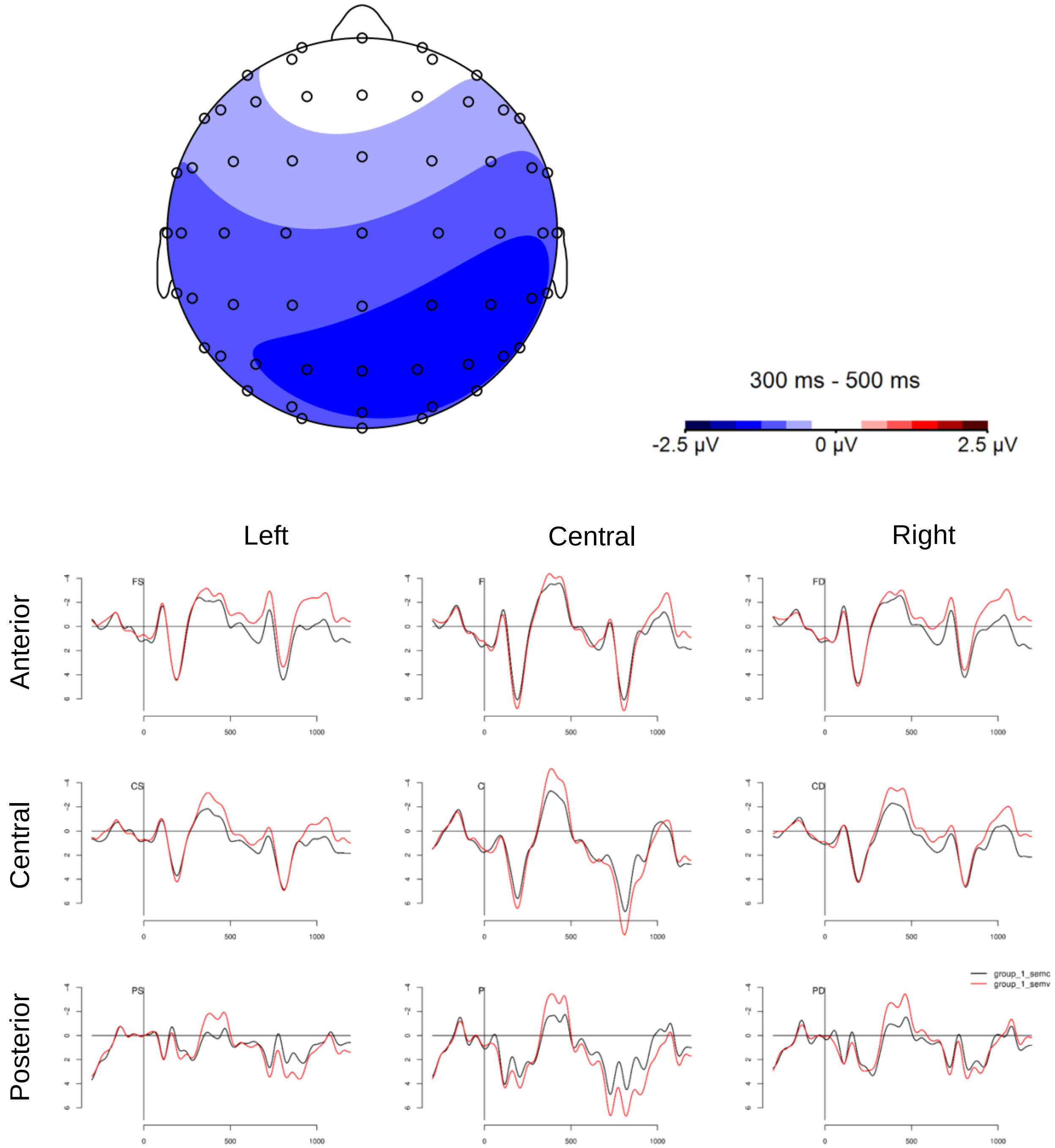

Figure 4.5 - ***A***) *Averaged topographic distribution of the N400 between 300 – 500 ms after the onset of the target word for group 1 (N=12). The scale ranges symmetrically from -2.5 to 2.5 µV.* ***B***) *Average of waveforms of participants from group 1 (N=12) in the 9 clusters of electrodes (described in captions of figures from 4.1 to 4.4) for the semantic condition. Correct condition is represented in black; violated condition is represented in red.*

Group 2

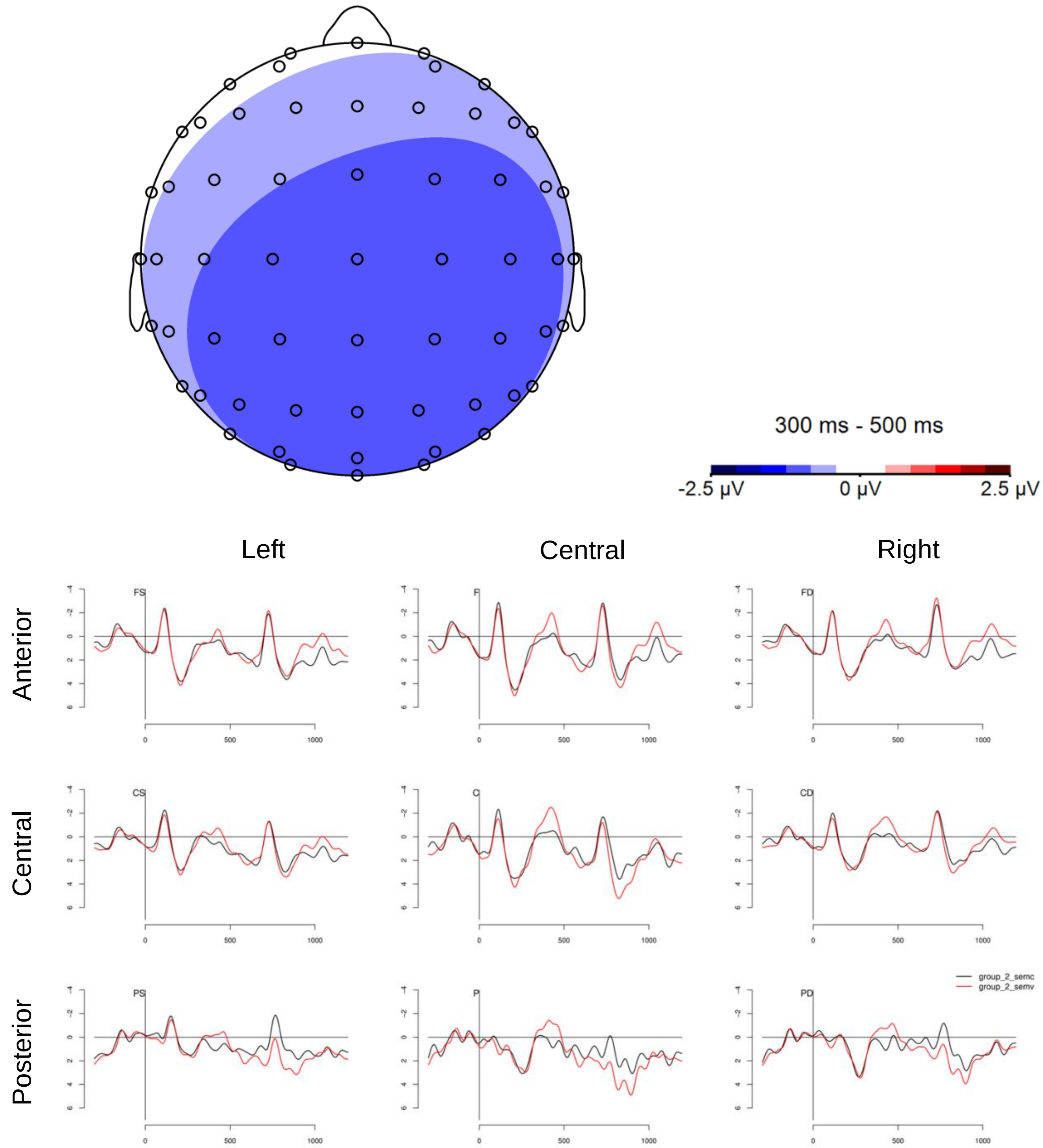

Figure 4.6 - ***A****) Averaged topographic distribution of the N400 between 300 – 500 ms after the onset of the target word for group 2 (N=12). The scale ranges symmetrically from -2.5 to 2.5 µV.* ***B****) Average of waveforms of participants from group 2 (N=12) in the 9 clusters of electrodes (described in captions of figures from 4.1 to 4.4) for the semantic condition. Correct condition is represented in black; violated condition is represented in red.*

Group 3

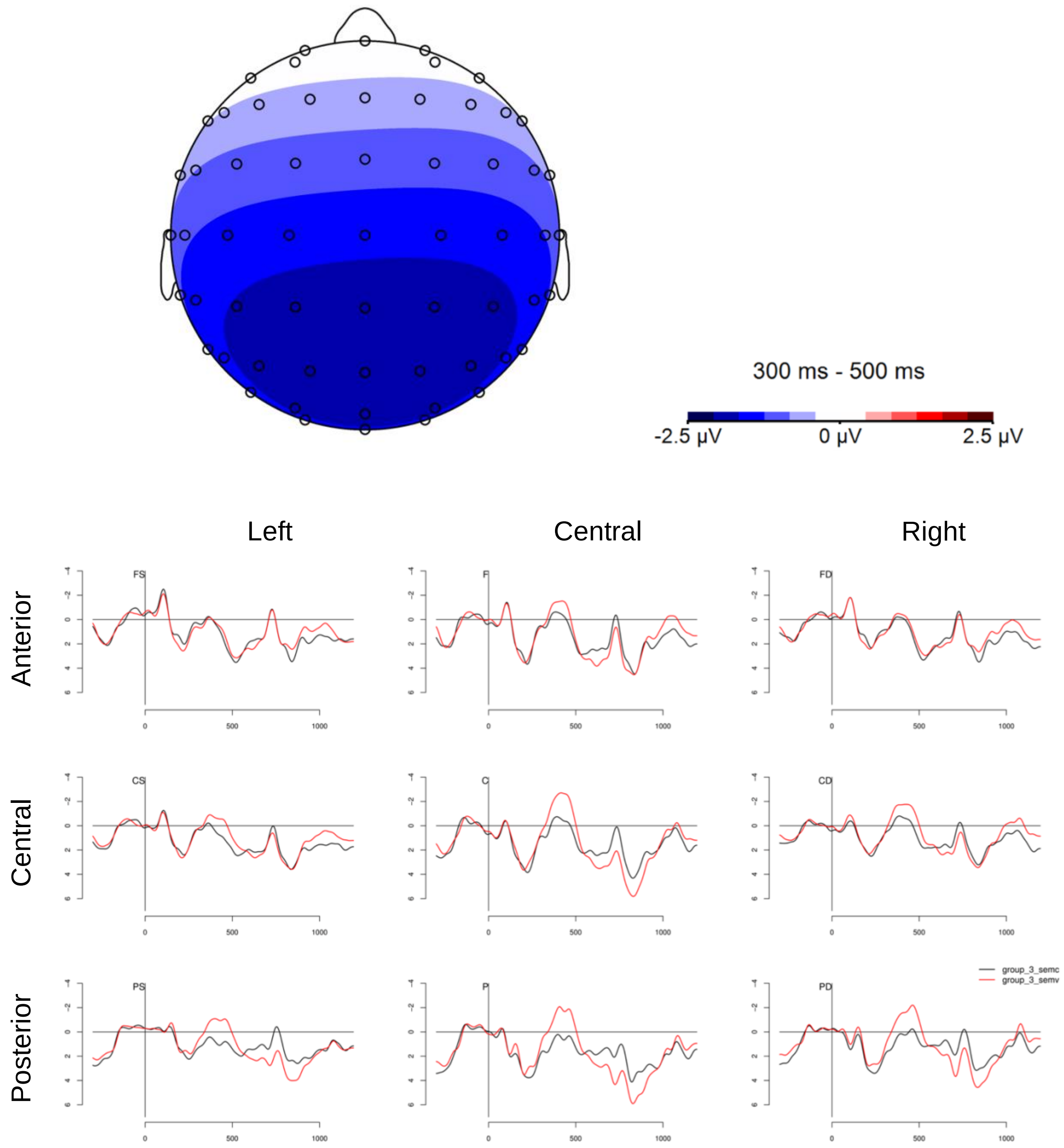

Figure 4.7 - ***A***) *Averaged topographic distribution of the N400 between 300 – 500 ms after the onset of the target word for group 3 (N=12). The scale ranges symmetrically from -2.5 to 2.5 µV.* ***B***) *Average of waveforms of participants from group 3 (N=12) in the 9 clusters of electrodes (described in captions of figures from 4.1 to 4.4) for the semantic condition. Correct condition is represented in black; violated condition is represented in red.*

Group 4

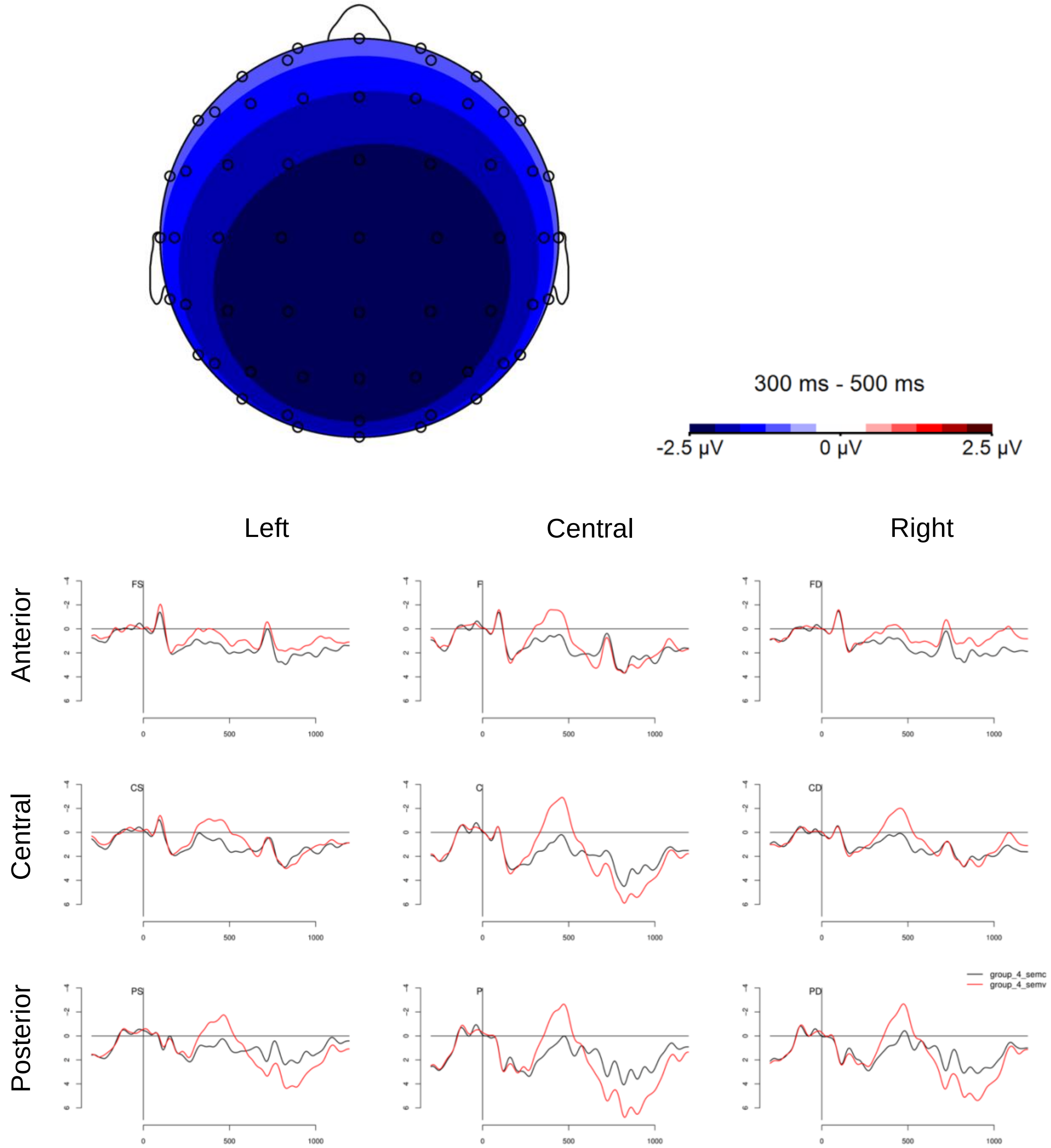

Figure 4.8 - ***A****) Averaged topographic distribution of the N400 between 300 – 500 ms after the onset of the target word for group 4 (N=12). The scale ranges symmetrically from -2.5 to 2.5 µV.* ***B****) Average of waveforms of participants from group 4 (N=12) in the 9 clusters of electrodes (described in captions of figures from 4.1 to 4.4) for the semantic condition. Correct condition is represented in black; violated condition is represented in red.*

4.6.1 – N400, Visual inspection

We performed a visual inspection of the averaged waveforms for the N400 (300-500 ms). All of the four groups exhibit a typical central-posterior distributed N400 effect that is also visible in the lateral lines, especially in the central-posterior clusters. However, the first group had both lines representing the correct and the violated condition, clearly in the negative area whereas from group 2 to group 4, this does not happen. Though, the difference of the amplitude between the two lines (correct & violated) remains almost unchanged possibly revealing stronger skills of semantic integration/access after the youngest ages that we tested.

4.6.2 – N400, Statistical Analyses

Results recorded after semantic violations were analyzed with a repeated measures ANOVA in the typical time window for the N400 (300 – 500 ms). We found a main effect of CORRECTNESS ($F(1, 44) = 44.03$, $p < .001$, $\eta_p^2 = .50$) and LONGITUDE ($F(1.28, 56.12) = 5.32$, $p = .018$, $\eta_p^2 = .11$). The main effect of GROUP barely missed the statistical significance threshold ($F(3, 44) = 2.56$, $p = .067$, $\eta_p^2 = .15$). We also registered the interaction between CORRECTNESS and LONGITUDE ($F(1.23, 54.27) = 6.67$, $p = .009$, $\eta_p^2 = .13$). No interactions with group were found (all F-values < 1.98).

After visual inspection, we decided to investigate the late positivity after the N400 that is clearly present across all the groups (see figures from 4.4 to 4.8). This late positive component resulted to be significant for CORRECTNESS ($F(1, 44) = 7.62$, $p = .008$, $\eta_p^2 = .15$) revealing that after the N400, the late positive component is also present and possibly associated to semantic processing.

4.5 – Discussion

With the present study we aimed to exploit the control data collected for the CI study (Chapters 5 & 6). The main purpose of this study was to validate the paradigm, proving to be reliable prior to the application of it to the clinical groups. Given the large number of participants collected and their homogeneous distribution over a large lifespan, we also were able to better understand the effect of age on evoked ERP components while reading sentences that contain semantic or syntactic violations. EEG from 64 channels was recorded in 48 normal developing participants that were divided in four age-range groups (12-17; 18-28; 29-44; 45-65 years old).

4.5.1 – Discussion, syntactic condition

We confirmed the expected effect of morphosyntactic agreement violation on the elicited ERP components: sentences with an embedded syntactic agreement violation elicited a typical P600 effect. The repeated measures ANOVA that we implemented with age-group as a categorical independent variable, showed no effect or interactions in the tested time windows (overall P600 and two-stages) with age-group factor, despite visual inspection suggested a different topography of the early stage of the P600 across age groups. Specifically, a main effect of correctness and longitude were found both centrally and laterally in the classic time window for the posterior P600, between 550 ms and 1050 ms after target stimulus onset. A main effect of group was found in the central line but not in interaction with correctness, suggesting that variations of ERPs were not specific to either correct or violated sentences. The analyses of the P600 split into an early and a late time window were performed because topographical variations across age-groups seem larger in the early stage of the P600. Even in this case, both along the central line and in the two lateral lines, we did not find any significant effect with group as factor. For the late P600, we found a main effect of group on the central line only with group one being the principal responsible for this result after visual inspection.

As for the LAN, the only significant effect in the 300 – 400 ms time interval including correctness was an interaction between laterality and correctness, again with no further qualification of the effect in terms of interaction with age-group factor. This despite the fact visual inspection strongly suggests consistent topographic variations of this component across the four groups of age.

Overall, the statistical analyses adopted here suggest a stability of the pattern elicited by syntactic violations across ages which is in contrast with visual inspection. Moreover, if the posterior P600 is a clear and reliable effect, the same does not apply for the previous negativity that, despite significant, seems small, rather variable and hard to be firmly described as a LAN, N400 or LTN (Left Temporal Negativity). On the basis of the results of individual-level analyses (see paragraph 3.3.5) in which we showed that the signal to noise ratio of our paradigm is rather good (at least for the posterior P600), we hypothesized that even a relatively small number of subjects (12 for each age group) would have allowed us to track age-dependency of ERPs effects elicited by syntactic violations. The fact that visual inspection suggests large numerical trends that are not confirmed by the statistical analyses does not allow us to take a strong position that assumes a stability of the pattern across age but rather suggest either that a larger sample of subjects or a different, possibly more explorative, data analysis approach should be adopted.

4.5.2 – Discussion, semantic condition

We confirmed the expected effect of meaning incongruity on the elicited ERP components: sentences with an embedded semantic violation elicited a typical centrally distributed N400 effect. Interestingly, we found a stronger negativity for the youngest group with both the correct and the violated sentences, eliciting a strong negative deflection. A similar result, with a peak in the N400 time window, also for correct sentences was already present in the literature where, it should be noted, the tested groups were up to twelve years old (Hahne et al., 2004) or from 6 to 7 years old, where after the age of 7 participants started to show adult-like activations (Holcomb et al., 1992). Hahne and colleagues (2004) interpreted this result as an effect of the major effort required by young subjects during the semantic integration while reading a sentence also for conditions that were coherent. On the other hand, given the frontal nature of the activations that Holcomb et al. (1992) found in their study, the interpretation was radically different. They hypothesized that the resulting component could have been the result of the superimposition of the classic N400 with a frontal independent component elicited in the same time window. Our end-of-sentence acceptability judgement supports the first theory with participants from group 1 performing slightly worse in the detection of the violation and/or correctness of sentences from the semantic set.

We also analyzed the effect of the cloze probability where the repeated measures ANOVA did not reveal any statistical difference between groups of age. However, in this case, the limited sample combined with the further division of the items between high and low cloze probability, might have played a major role in the lack of significance. Group 1 (from 12 to 17 y.o.) seems to show a stronger difference between the correct and the violated conditions for the sentences in the high cloze probability set. In low cloze probability sentences, target words that are coherent with the context (correct condition) seem to elicit the same potential of sentences with a violation embedded. Still relying on visual inspection, the same effect appears to be present, despite being less strong, also in the second group of age (from 18 to 29 years old). Interestingly, this effect disappears starting by group three and remains absent in the fourth group as well. In these two age ranges, the difference between the semantically correct and violated conditions is clear for both high and low cloze probability sentences. One possible explanation for this result could be that young people are less capable in the anticipation of an upcoming word while reading. The lack of linguistic experience (in terms of years of exposure) can impact the ability of participants to predict words given the context provided by the beginning of the sentence.

5.0 – Written sentence processing in Preverbal CI Users

5.1 - Introduction

In this study we used classic EEG methods to examine to what extent cochlear implantation can promote the development of typical neural responses evoked by lexical-semantic or morphosyntactic violations during sentence processing.

Deaf children, particularly those born from hearing parents, are at risk of severe underexposure to language during the critical period for its acquisition. The advent of cochlear implants has had a tremendous impact on deafness, allowing people with severe sensorineural deafness to partially recover acoustic information. Given the possibility to provide children with an implant very early in life (even before 6 months of age), it is often assumed that the risk of an underexposure to language is efficiently contrasted by the advent of this neuroprosthesis. However, the variability in the outcomes and the quality of the signal strongly depend on clinical and anamnestic variables that have only partially been identified (Pisoni et al., 2018). Furthermore, it is extremely challenging to assess how preverbal deafness onset individuals perceive sounds and voices, making hypothesis on the quality of the heard spoken signal difficult. Therefore, it is crucial to investigate to what extent preverbal CI users can achieve levels of language development comparable to those of their hearing peers.

As outlined in Chapter 1, much of what we currently know of language development in preverbal CI users has emerged from behavioral investigations, typically concerned with processing of language in the re-afferented auditory modality, and often focused on understanding of single words. Here, we took a substantially different approach, probing the integrity of language in preverbal CI users adopting (1) short sentences rather than single words to unravel the integrity of language at the level of sentence processing; (2) a combination of EEG and behavioral methods; (3) stimuli delivered always through an intact sensory system (vision).

Specifically, we built an experiment based on a well-established paradigm in the psycholinguistics literature. We prepared a set of sentences containing embedded incongruities that were either semantic or syntactic aiming to replicate findings that revealed an N400 and a P600 effect in response to the two violations respectively. Sentences were presented visually, one word at a time, on a computer monitor while recording EEG signal. Participants were required to carefully read each sentence and to judge at end of each one whether they perceived it as acceptable or not by pressing one of two buttons. We expected to see the classic N400 and P600 in response to semantic and syntactic violations in control subjects. In deaf CI users we expected comparable N400 with normal hearing participants with possibly a different modulation of the P600 component compared to controls. We doubled the number of the trials per condition which should allow us to reliably be able to detect components at individual-subject level.

This approach is innovative in many different ways. First, we focused on sentence processing, rather than single words, using EEG. By switching from single words to a sentence level means that we were able to investigate language at a higher level introducing a syntactic structure in our paradigm.

Second, although several studies have examined sentence processing in deaf people with CI, to date there has been very few investigations that examined this with EEG. The first relevant advantage of using EEG is the nature of the event-related potential technique itself being the best choice in order to have reliable real-time data reflecting neural processes that happen in the subject's brain. We aimed to work on data recorded during sentence processing itself and not by analyzing the behavioral response without real-time brain activations. In this way, we had both: EEG data from the scalp with event-related potentials locked on the critical word and behavioral measure at the end of the sentence which should not have interfered with the online task.

The third advantage is that, all delivered stimuli (i.e. words) in our paradigm were presented visually, one word at a time, for the same amount of time. The chance that the participants do not actually process all of the presented words is still present. In fact, top-down reading mechanisms where short words or morphemes are often neglected, can have an impact on the perception of above-threshold stimuli, even on an intact sensory system. This aspect alone, can be considered as a viable way to explore the integrity of sentence analysis mechanism. This is particularly important when considering the unbalance that content words (i.e. nouns, adjectives, verbs, etc.) and function words (i.e. clitics, pronouns, etc.) have in the way deaf and hard-of-hearing people process language, with the first being easier and therefore more prone to be perceived by these populations. Furthermore, this approach allows to disentangle between difficulties that pertain to language processing in people with CI and those linked to the quality of the acoustic information that their implants deliver. Processing difficulties can be easily confounded when the used stimuli are auditory stimuli (see for an example: Hahne, Wolf, Müller, Mürbe, & Friederici, 2012). By passing through an impaired pathway we cannot be sure how well and to what degree each participant perceives the acoustic stimuli through the implant. This would have introduced an enormous amount of noise in our group which is surprisingly homogeneous compared to other works in the literature (Mehravari et al., 2017).

Fourth, as mentioned before, we aimed to obtain EEG measures that are reliable at single-subject level. To this aim, we did duplicate the number of the stimuli usually employed in other similar studies that used forty/fifty items per condition (Barber & Carreiras, 2005; Gunter, Friederici, & Schriefers, 2000; Hagoort, 2003; Hagoort & Brown, 1999; Hinojosa, Martín-Loeches, Casado, Muñoz, & Rubia, 2003; Kaan, 2002; Kaan & Swaab, 2003; Martín-Loeches, Nigbur, Casado, Hohlfeld, & Sommer, 2006; Molinaro, Vespignani, et al., 2011; Osterhout, McKinnon, Bersick, & Corey, 1996; Silva-Pereyra & Carreiras, 2007) or in comparison to other studies that employed less than 40 items per condition (Hagoort & Brown, 2000; Kaan et al., 2000; Molinaro et al., 2008; Nevins, Dillon, Malhotra, & Phillips, 2007). Each subject saw 320 sentences divided in 2 subsets: one for the semantic, and one for the syntactic investigation. Both subsets had half of the items containing a violation and half acting as the control condition. As previously mentioned, with a total of eighty items per condition, our experiment exceeds the usual number of items used for reliable data at group level. The aim is to examine the relation between the EEG components and the anamnestic/clinical variables that characterize each participant – in particular those related to auditory re-afferentation with cochlear implant.

Our predictions were as follows: first, we expected to find comparable N400 responses to lexical-semantic violations. We didn't expect differences at group level in the semantic processing as it has been proven that deaf and hard-of-hearing individuals, do strongly rely on semantic features of language. Furthermore, previous results in the literature showed that the processing of semantic incongruities were affected neither by deafness (Mehravari et al., 2017) nor by language acquisition modality (Hänel-Faulhaber et al., 2014; Skotara et al., 2011). At single subject level, we did not expect any particular correlation between the N400 and individual variables although the exposure to language and the wealth of the individual vocabulary may play a role in the modulation of the N400 with this last one being positively correlated with higher level of linguistic skills. Moreover, we divided the semantic set of stimuli in high and low cloze probability sentences which allows us to distinguish the effect of expectancy (by analyzing correct high vs. low cloze probability items) from the violation alone that can be analyzed by contrasting high vs. low cloze probability sentences in the violated condition. This manipulation is valid for both controls and CI users in either group or single-subject level.

On the other hand, we did expect differences in the syntactic processing signature represented by the P600 component. Despite being very well established in the literature about morpho-syntactic anomalies (Coulson, King, & Kutas, 1998; De Vincenzi et al., 2003; Osterhout & Mobley, 1995; Silva-Pereyra & Carreiras, 2007), the P600 is also prone to be affected by language exposure as a representation of the ability to normally process an agreement violation. We expected the P600 to be present but possibly smaller or modulated by individual variables such as age at first implant or with behavioral measures of morpho-syntactic sensitivity and skills.

5.2 – Methods

5.2.1 – Participants

Thirteen normal hearing controls (8 female; mean age = 16.8 years, age range: 12-24 years) were selected for their ages to match as closer as possible the CI users' group (mean difference between groups = 0.2 years, SD = 3.51). Participants from this group were recruited through our local digital-recruitment system and by word of mouth. All control participants reported to have normal hearing and none of them was familiar with Sign Language. Control group went under the same procedure as the CI group with the obvious exception of the clinical section of the anamnestic questionnaire. Control participants passed all the EEG preprocessing steps (see §) retaining on average 98% of the total epochs (98% of the epochs in the semantic condition; 98% of the epochs in the syntactic condition; average of 78.67 items out of 80; SD=1.59).

Fourteen early-deaf CI users were recruited to take part in the study (≥85db Hearing level (HL) in each ear). Six of them were recruited thanks to the agreement with the local Hospital. The remaining eight participants were recruited though our connection with the Cooperativa Logogenia® that operates in the north-east of Italy with the aim to apply the generative approach to the grammar with young deaf and non-normal developing children (Franchi & Musola, 2012); five of them were tested in the Milan area in one of the cooperative office. Thorough information about the clinical history (e.g. age at diagnosis, age at implantation, hearing residuals, hearing aids: presence and outcome, etc.) were provided by the hospital for 9 participants. For the remaining 5 participants we used information provided by parents since all of those subjects were underage.

With the cochlear implant switched off, all deaf participants had a diagnosed bilateral profound deafness with no usable residual hearing. One CI user had to be discarded from the analyses because she showed excessive artifacts during the EEG recording session, leaving too few usable epochs to be analyzed. All remaining participants (7 female and 6 men; mean age = 16.5 years, age range: 12 – 24, p = 0.87) passed all the EEG preprocessing steps (see paragraph 3.2.5) retaining on average 91% of the total epochs (90% of the epochs in the semantic condition; 92% of the epochs in the syntactic condition; average of 72.83 items out of 80; SD = 8.87). All of our CI users were proficient cochlear implant users: they all reported to use it for the entire duration of the day and none of them reported to ever have had issues with the implant. Qualitatively reporting, we were always able to easily speak with them without any problem, most of the time even when they were not in front of us therefore precluding the possibility of lip-reading and by being outside of the cone where usually microphone's directionality is pointed at. Audiological data provided from the hospital confirmed that all of our participants experienced a very good outcome after implantation both from an audiometric and from a linguistic point of view (all participants recruited through the local hospital (Ospedale Santa Maria del Carmine, Rovereto TN, Italy) were followed by an internal speech therapist who provided us with this post-implant information. Eleven CI users out of thirteen have had experience with hearing aids (HA) before switching to cochlear implant. For further information and more detailed data, consult Table 3.1.

CI users completed an anamnestic form aimed at collecting personal information (e.g., age, current job, education, etc.) as well as project-relevant clinical information (e.g., deafness onset, age at implantation, hearing aid, etc.). For eight CI users it was possible to confirm or correct these clinical data with those provided by the hospital. For the remaining five CI users the information was obtained from either available clinical documentation or self-report. NH controls were also asked to complete the section of the questionnaire concerning personal information. When the participant was underage, we asked parents to fill or to help their son to complete the questionnaire.

None of participants reported any neurological problems and all of them had normal or corrected-to-normal vision. Importantly, neither CI users nor NH controls reported experience with sign language.

ID	*Sex*	*Education (yrs.)*	*Age (yrs.)*	*Deafness onset (months)*	*N. of CI*	*Age at implantation (months)*	*Hearing aids*
*CI-pre1**	F	11	16	13	2	36	Y
*CI-pre2**	F	11	16	13	2	33	Y
CI-pre3	F	7	12	18	2	32	Y
CI-pre4	F	9	14	18	2	36	Y
CI-pre5	M	10	15	27	2	96	Y
CI-pre6	F	8	13	0	1	48	Y
CI-pre7	F	8	14	12	2	24	N
CI-pre8	F	11	17	0	2	24	N
*CI-pre10**	M	11	17	27	1	42	Y
*CI-pre11**	M	16	24	12	1	33	Y
*CI-pre12**	M	12	18	12	1	27	Y
*CI-pre13**	M	10	16	6	1	16	Y
*CI-pre14**	M	13	23	6	2	36	Y

Table 3.2 – *Selected information about deaf individuals who participated in the study. This information is coming from both the questionnaire they were required to complete after the EEG session and/or from information provided by clinicians at the hospital (where applied *). "CI-pre9" is not listed because she was excluded from all analyses.*

The experiment was carried out in compliance with the Helsinki Declaration. The ethics committee of the University of Trento (CESP) approved the study (reference number: 2014-029). At the very beginning of the recruitment participants were instructed about the voluntary nature of the participation to the experiment and that they would have been able to leave the experiment at every moment. Before the beginning of the experimental session they were provided with the informed consent, the privacy management policy and with a thorough written explanation of the EEG technique. They had to sign their approval for the first two modules described above.

When the participant was underage, we required the approval of both parents and we also asked minors to sign an assent module specifically formulated for them. Given the relatively advanced age of minors, despite being legally not valid, we agreed not to test underage candidates if their assent was not provided.

5.2.1 – Stimuli, procedure and apparatus

Stimuli, procedures and apparatus employed in this study were described in the third chapter (see Chapter 3). No deviation from the main paradigm was made and any peculiarity about the application of the aforementioned procedure for this specific study, when present, will be explained.

5.3 - Results

5.3.1 - Behavioral measures

All subjects were required to take part to behavioral measures previously described. We grouped the tasks in a lexical-semantic and morpho-syntactic cluster following the domain that was involved. Specifically, the semantic cluster included: The Semantic Fluency task (SFT) and the Lexical Decision task (LDT). On the other hand, in the syntactic group of tests we included: The Sentence Picture Matching task (SPM), the Grammaticality Judgement task (GA) and the Error Detection task (ED). Furthermore, participants were also required to provide an acceptability judgement at the end of each sentence during the EEG experiment which is part of the behavioral measures. For this task also, we divided analyses and results for the semantic and the syntactic condition.

5.3.1.1 – Behavioral measures – End-of-sentence acceptability judgement

Here we analyzed the acceptability task at the end of each sentence during the EEG session. Compared to hearing controls, deaf CI users were less sensitive to both semantic (Wilcoxon, p = 0.0021) and syntactic (Wilcoxon, p = 0.012) violations, with greater score dispersions for CI users (range: 0.33 – 4.73) compared to controls (range: 2.33 – 5.23) (see Figure 5.1).

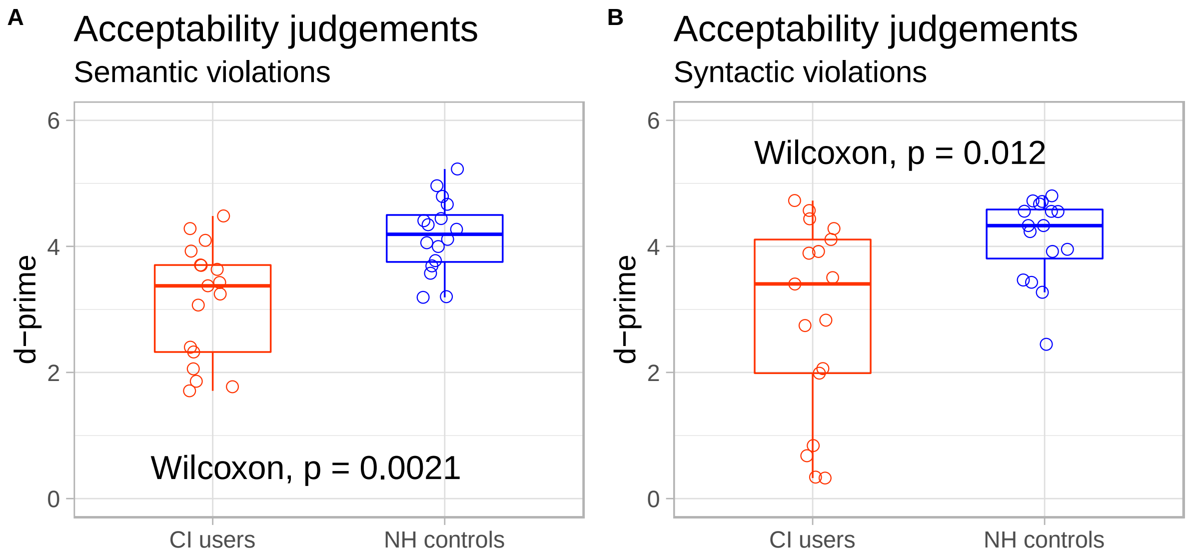

Figure 5.1 – ***A***) *d-prime index calculated for CI users (in red) and normal hearing controls (in blue) for the end-of-sentence acceptability judgement task in the semantic condition.* ***B***) *d-prime index calculated for CI users (in red) and normal hearing controls (in blue) for the end-of-sentence acceptability judgement task in the syntactic condition. Data points represent single subject's data.*

Prior to the d-prime analysis, we also calculated the number of the answers that have been provided by participants at the end of each sentence during the EEG experiment. This index, although not as informative if compared to the d-prime, could give us some information concerning the confidence of participants when presented with the acceptability question at the end of each trial. CI users omitted higher number of responses compared to controls both in the semantic condition ($p = 0.001$) and in the syntactic condition ($p = 0.003$). Omitted responses at the end of the sentences during EEG can have multiple explanations: it could reflect lower ability to detect and retain the information about the correctness of the sentence; or it can indicate higher response times given that they only had 2 seconds to give the response before the fixation cross appeared on screen. It is worth noting though, that despite CI users were significantly worse compared to control participants, the average percentage of given responses was still higher than 90% which provided us with enough data for the analyses. Specifically, normal hearing controls provided an average of 98% of responses.

5.3.1.2 – Behavioral tests - Semantic set

CI users performed statistically different from normal hearing controls when we measured the accuracy in the lexical-decision task (Wilcoxon, $p = 0.0087$) and they showed slower response times (Wilcoxon, $p = 0.012$) in the same test possibly reflecting a less good vocabulary knowledge and consequently slower lexical access compared to controls (see Figure 5.2).

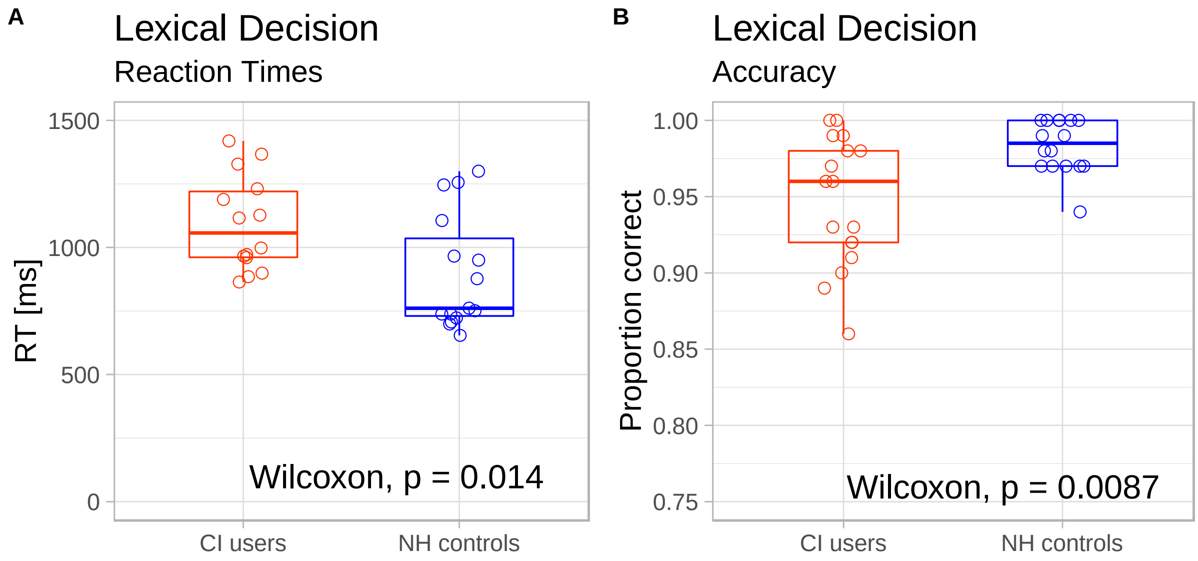

Figure 5.2 – ***A****) Reaction times of CI users (in red) and normal hearing controls (in blue) in the lexical decision task.* ***B****) Proportion of correct responses of CI users (in red) and normal hearing controls (in blue) in the lexical decision task. Both accuracy and reaction times are significantly better for the NH-controls compared to CI users. Though, it should be noted that more than half of the CI users are within the range of NH-controls for accuracy. Data points represent single subject's data.*

The semantic fluency task revealed the same pattern with CI users performing slightly worse than hearing controls (Wilcoxon, $p = 0.0039$) confirming the pattern that overall, CI users are slightly less efficient in accessing the lexicon (see Figure 5.3).

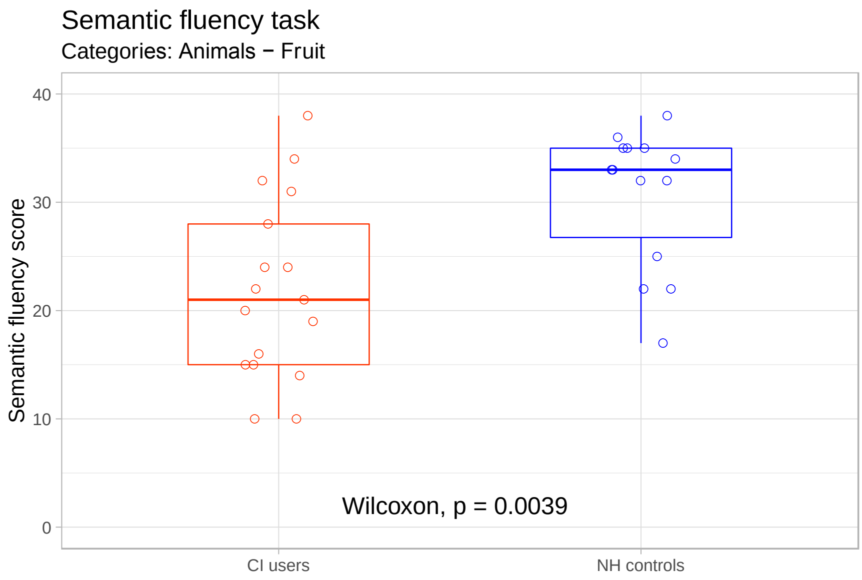

Figure 5.3 – *Total number of pronounced words during the semantic-fluency task. CI users (in red) and normal hearing controls (in blue) did show a significant difference where most of the CI users pronounced less words than NH-controls. Data points represent single subject's data.*

5.3.1.3 – Behavioral tests - Syntactic set

The grammatical accuracy task confirmed again the previously found trend in the semantic cluster of measures, with CI users showing a slightly worse performance compared to hearing controls (Wilcoxon, $p = 0.031$). Although the average performance emerged to be worse in CI users, it should be noted that the overall level of performance is rather high for CI users as well with the majority of participants performing at above 90% of accuracy. Still, this result, combined with the end-of-sentence acceptability judgement reveal a numerically small but statistically significant weakness of early deaf CI users in the processing of syntactic features when reading written sentences (see Figure 5.4).

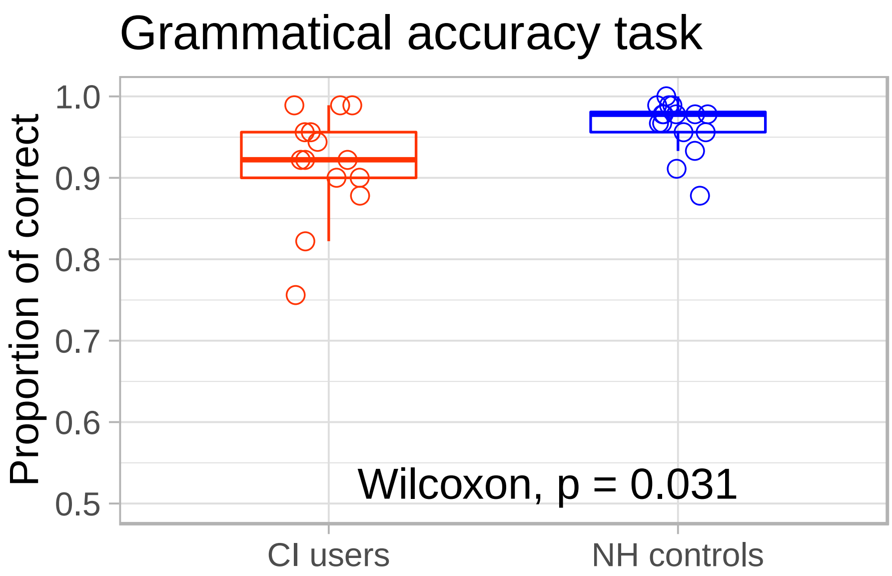

Figure 5.4 – *Proportion of sentences that have been correctly judged by CI users (in red) and NH-controls (in blue). Although the performance is very high in both groups, the statistical comparison between the two populations revealed significant difference (p = 0.031) with CI users performing worse than hearing controls. Data points represent single subject's data.*

The sentence picture task revealed a slightly more detailed picture of the syntactic skills of our CI users. We expected worse performances if CI users in the conditions where we applied a manipulation that aimed to make the syntactic structure or the task harder. In fact, CI users performed statistically similarly with controls in categories one, two, five and six with "p" never exceeding 0.14 (see Figure 5.5 for each statistical analysis). However, as predicted, CI users showed weaker performances in category 4 (Wilcoxon, p 0.014) and a drastic drop in the performance for some of participants in category 3 (Wilcoxon, p = 0.0061). The third category contained short sentences with implicit postverbal subject [PRO$_{+pl+object}$ gives the grandmother $_{+subject}$) which we predicted to be the hardest condition for CI users.

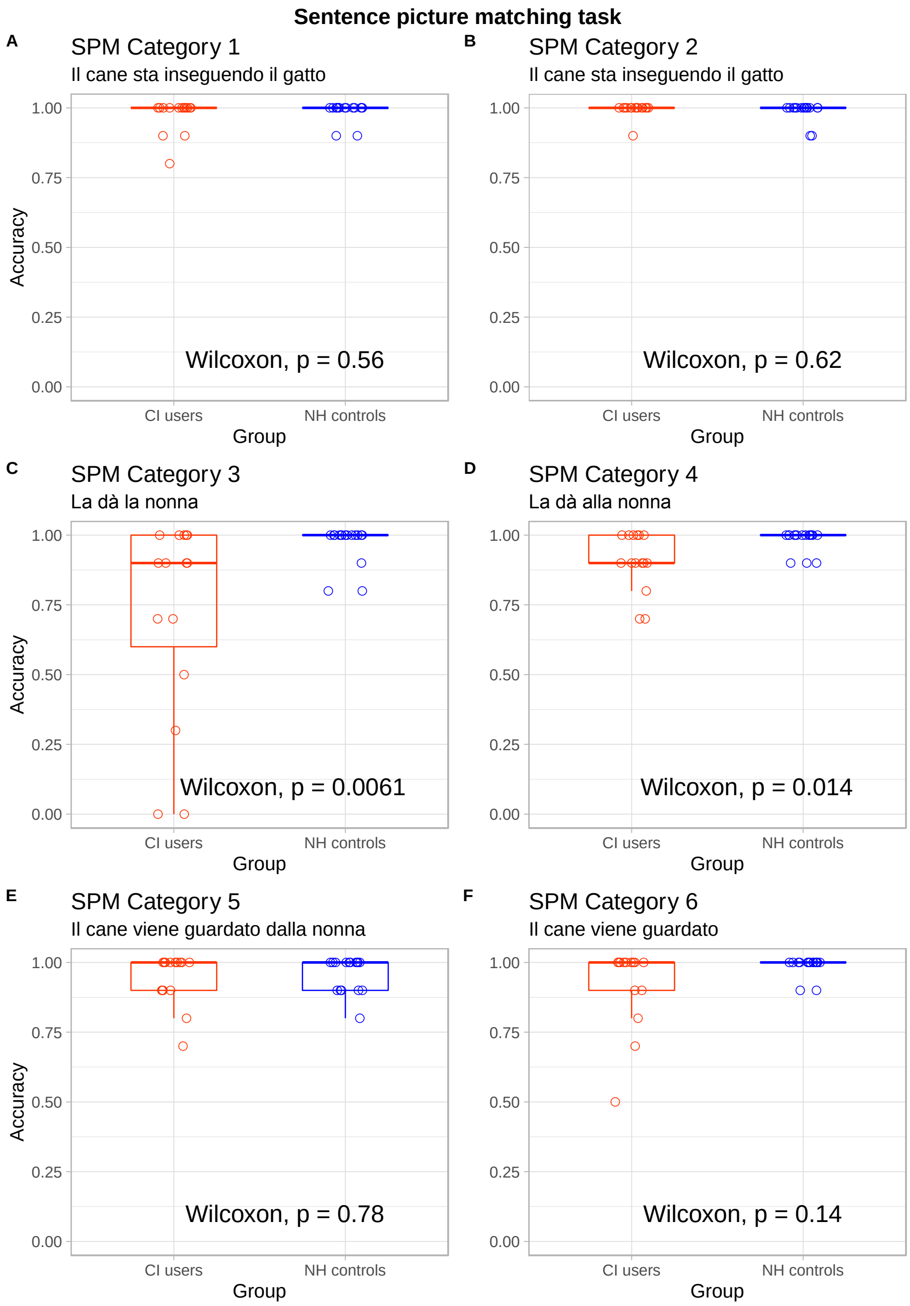

Figure 5.5 – *Accuracy of CI users (in red) and NH-controls (in blue) in the 6 categories from 1 (**A**) to 6 (**F**). Significant difference was found between groups for both category 3 and 4 with the first resulting, as expected, the most challenging for CI users. Data points represent single subject's data.*

This result is suggesting that the syntactic weaknesses showed by CI users may be related to some specific structures that are present in the Italian language.

The error detection task again confirmed previous results by showing greater variability in the CI users' group. Specifically, they performed the same as NH controls in the detection of orthographic errors (Wilcoxon, p = 0.7). Statistically, they also did not show any difference in the syntactic errors' detection (Wilcoxon, p = 0.069). However, in the latter we can clearly see a much wider range of performances by CI users compared to NH controls. Statistically different were the performances in the morphosyntactic errors' detection (Wilcoxon, p = 0.0058) and in the overall performance where CI users showed an overall drop in the performances compared to NH controls (Wilcoxon, p = 0.019) (see Figure 5.6).

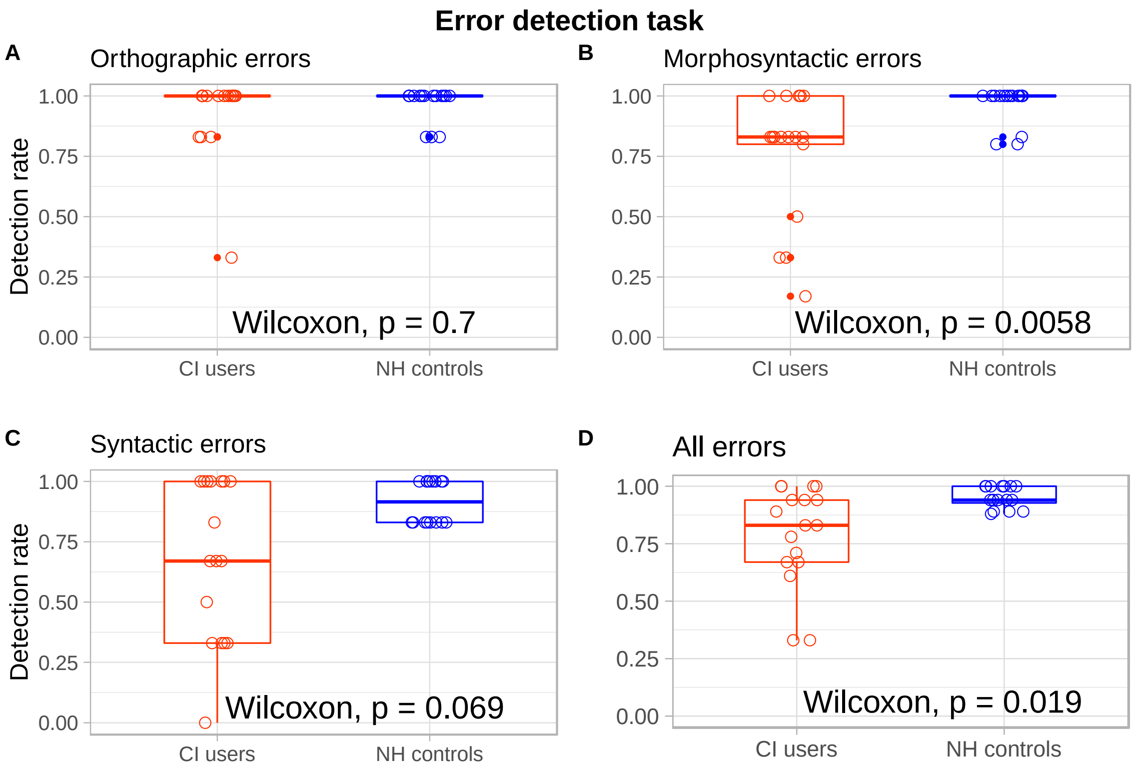

Figure 5.6 – *Proportion of orthographic (**A**), morphosyntactic (**B**), syntactic (**C**) and all (**D**) errors correctly detected by CI users (in red) and normal hearing controls (in blue) in the lexical decision task. Overall, CI users performed worse than NH-controls with a significant difference in the detection of morphosyntactic errors (p=0.006). Qualitatively, but not supported by statistical analysis, a much higher variability is also showed by CI users in the detection of syntactic errors. Data points represent single subject's data.*

5.3.2 – Comparable P600 in CI users compared to hearing controls

The key question of our work concerns the P600 response evoked when reading the set of sentences containing syntactic violations. This neural response is maximal over central and posterior electrodes, along the median line. To compare this component between CI users and NH controls, we pooled medial electrodes into three separate clusters (see Figure 5.7), averaging the EEG signal in the interval 550-1050 ms.

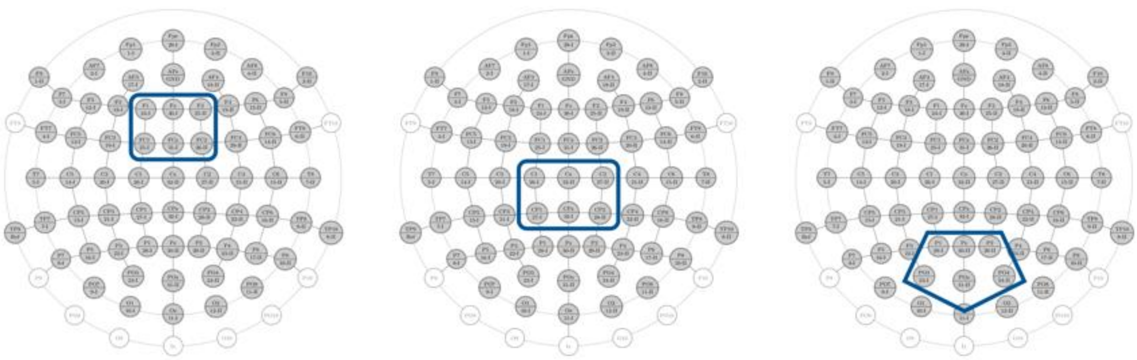

Figure 5.7 – *Electrodes clusters for the analyses along the central line: anterior: F1, Fz, F2, FC1, FCz, FC2; central: C1, Cz, C2, CP1, CPz, CP2; and posterior: P1, Pz, P2, PO3, POz, PO4.*

Resulting values were entered into an ANOVA with correctness (correct or violated) and longitude (frontal, central and posterior) as within-participants variables, and group as between-participant variable. This analysis revealed a main effect of CORRECTNESS (F(1, 24) = 26.43, p < .001, η_p^2 = .52), LONGITUDE (F(1.49, 35.82) = 4.91, p = .021, η_p^2 = .17) and the interaction between CORRECTNESS and LONGITUDE (F(1.12, 26.83) = 16.58, p < .001, η_p^2 = .41). Critically, no significant main effect or interaction involving the GROUP factor emerged (all F-values < 2.04).

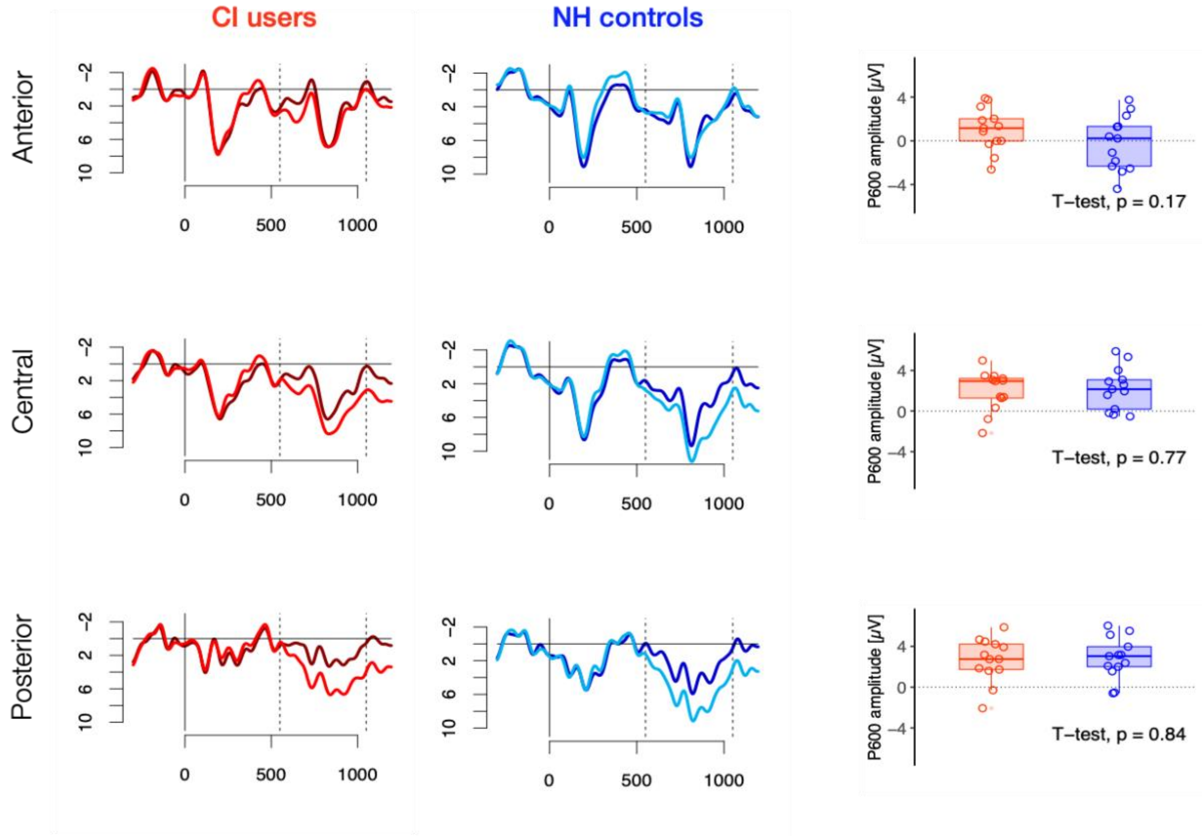

Figure 5.8 – *Averaged waveforms of the P600 (time window between 550 and 1050 ms) responses (left) after stimulus onset in CI users (in red) and normal hearing controls (in blue) for anterior, central and posterior clusters along the central line. Control sentences are represented by the darker line while sentences that contain a violation are displayed with the lighter line. On the right, t-test comparison between CI users (in red) and controls (in blue) for the P600 amplitude (violated condition minus correct condition) expressed with positive values.*

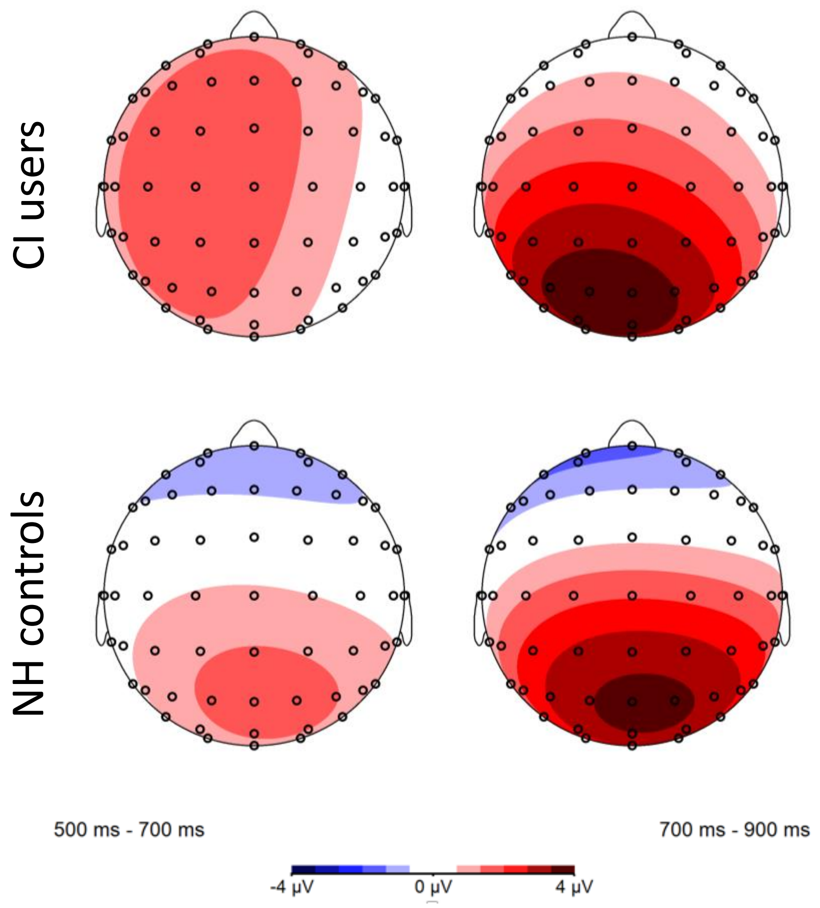

Figure 5.9 – *Averaged topographic distribution of the P600 between 500 – 700 & 700 – 900 ms after the onset of the target word for CI users on the top (N=13) and NH controls on the bottom. The scale ranges symmetrically from -4 to 4 µV.*

5.3.3 – Larger N400 in CI users compared to hearing controls

Having established comparable EEG responses in the two groups in sentences containing syntactic violations, we turn to study evoked components in the set of sentences containing semantic violations. We focused on the N400 component, which is typically maximal over central and posterior electrodes along the median line. To analyze this component, we used the same clusters (anterior, central and posterior) identified above, and averaged the EEG signal in the interval 300-500 ms. Figure 5.10B shows EEG responses to correct and violated sentences for each cluster, separately for CI users and NH controls. N400 amplitude values were entered into an

ANOVA with correctness and longitude as within-participants variables, and group as between-participant variable. This analysis revealed a main effect of CORRECTNESS ($F(1,24) = 25.17$, $p < .001$, ηp2 = .51) and the interaction between CORRECTNESS and LONGITUDE ($F(1.43, 34.26) = 4.20$, $p = .035$, $\eta_p^2 = .15$). Notably, the main effect of group ($F(1,24) = 4.87$, $p = .037$, $\eta p^2 = .17$) as well as the interaction between group and CORRECTNESS ($F(1, 24) = 6.29$, $p = .019$, $\eta p^2 = .21$) reached significance. N400 amplitude was larger in CI users (M±SD µV) compared to NH controls (M±SD µV), irrespective of cluster (see Figure 3B for box-plots and individual N400 amplitudes for each group and cluster). Scalp topography indicates that the effect is classically confined to central-posterior electrodes in NH controls, but more broadly distributed in CI users possibly causing the observed increase in N400 amplitude for this group.

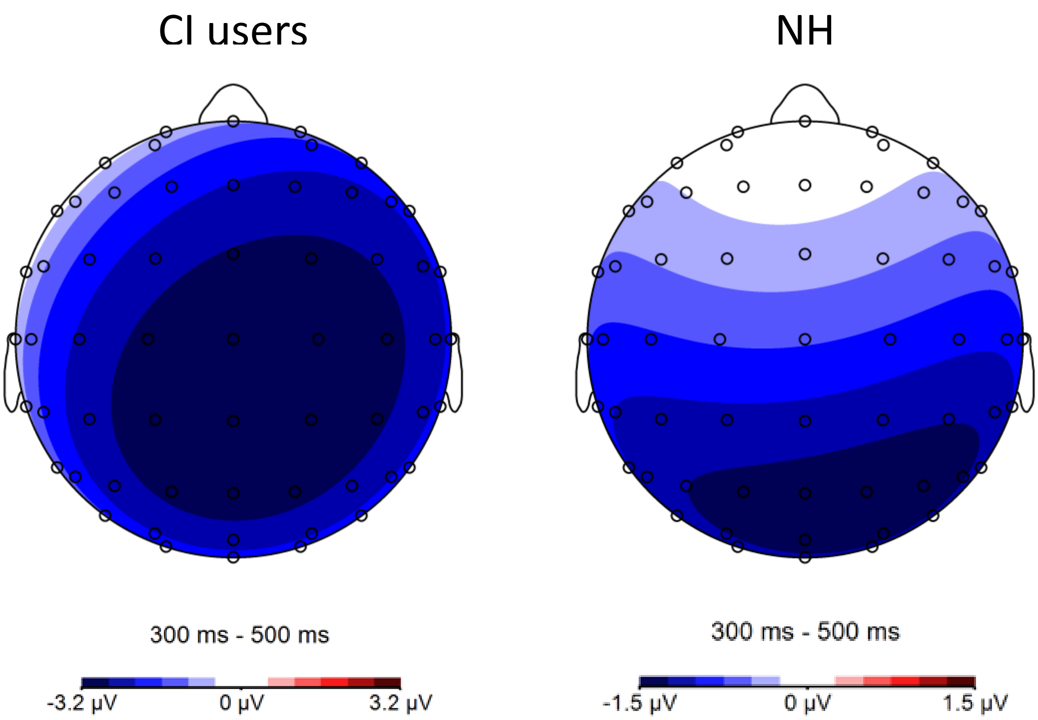

Figure 5.10 ***A*** – *Averaged topographic distribution of the N400 between 300 – 500 ms after the onset of the target word for CI users on the left (N=13) and NH controls on the right (N=13). For display purposes,* <u>*scales are not equal*</u> *between groups: -3.2 to 3.2 µV for CI users and -1.5 to 1.5 µV for NH controls.*

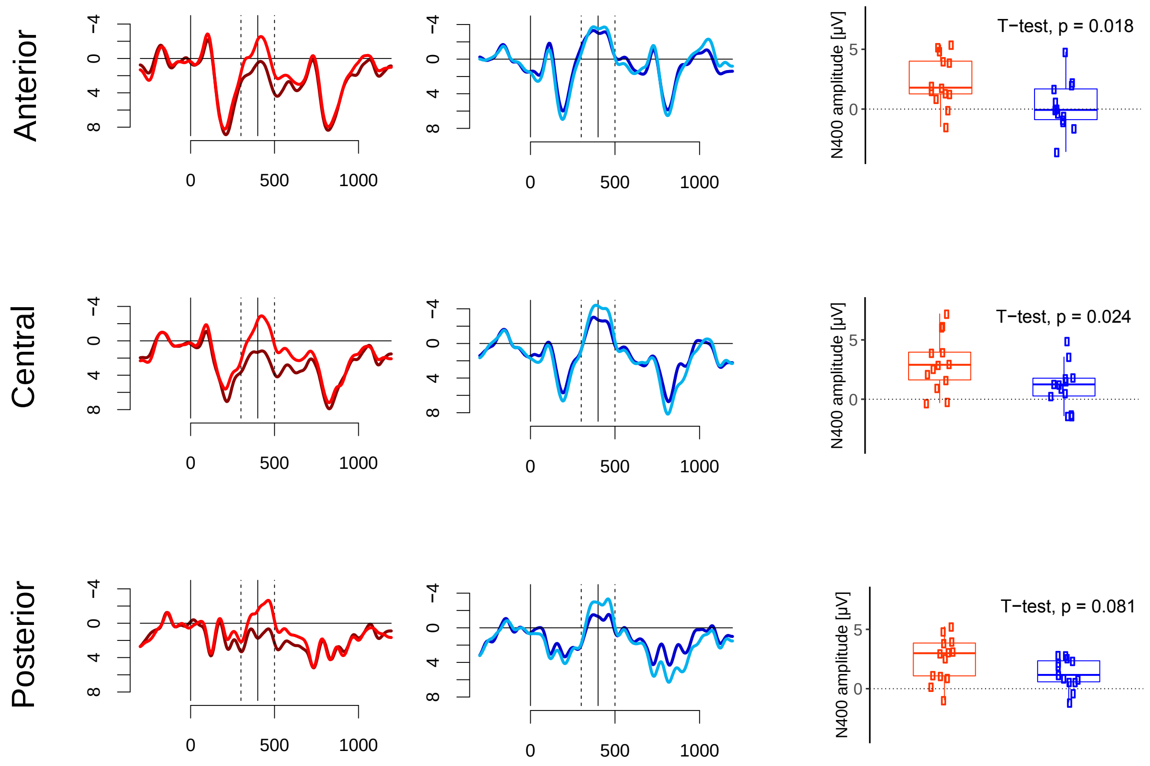

Figure 5.10 B – *Averaged waveforms of the N400 (time window between 300 and 500 ms) responses (left) after stimulus onset in CI users (in red) and normal heraring controls (in blue) for anterior, central and posterior clusters along the central line. Control sentences are represented by the darker line while sentences that contain a violation are displayed with the lighter line. On the right, t-test comparison between CI users (in red) and controls (in blue) for the N400 amplitude (violated condition minus correct condition) expressed with positive values.*

Semantic sentences in our experiment differed in cloze-probability (CP) level, depending on whether the semantic context was highly constrained (e.g., "Il meccanico ripara il MOTORE del camion." [The mechanic repairs the ENGINE of the truck.]; high CP) or poorly constrained (e.g., "Il negozio è fornito di sciarpe marroni". [The shop is supplied with brown scarf.]; low CP). Mean ERPs in correct and violated semantic sentences as a function of CP and group are reported in Figure 5.12. An ANOVA with correctness, cloze probability and group as factors revealed a significant two-way interaction between correctness and CLOZE PROBABILITY and GROUP ($F(1,24) = 6.52$, $p < .02$, $\eta_p^2 = 0.21$) (see Figure 5.12).

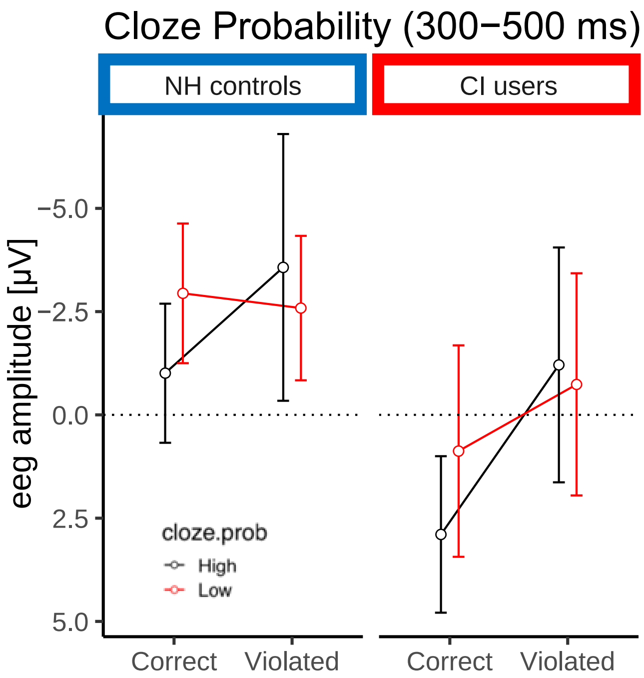

Figure 5.12 - *EEG amplitude in micro Volt (µV) for correct and violated sentences on the x-axis divided for normal hearing control (in blue on the left) and CI users (in red on the right). The black line represents the high cloze-probability condition and the red line represents the low cloze-probability. Cloze probability was run only among the semantic set of sentences and was analyzed in the time window between 300 and 500 msec after stimulus onset. This plot represents an average of the central cluster along the central line (Cz and the 8 electrodes around it).*

Contrasting N400 amplitude effects for correct vs. violated semantic sentences in low CP stimuli alone, allows to isolate the effect of *semantic violation* from expectancy. It has been suggested that CI users and deaf individuals rely on lexical-semantic features to a greater extent when processing language (Caselli et al., 2012; Duchesne, Sutton, & Bergeron, 2009; Geers et al., 2009; Niparko et al., 2010). If this is the case, we should observe larger effects of semantic correctness in low CP sentences for CI users compared to NH controls. An ANOVA with CORRECTNESS and GROUP as factors, revealed instead no significant two-way interaction ($F(1,24) = 1.52$, p < .23) indicating that in both groups semantic incongruencies alone were not sufficient to elicit differential ERPs. Contrasting EEG amplitude for high vs. low CP in correct sentences alone, allows instead to isolate the effect of *expectancy* violation from semantic incongruency. To examine this aspect, we entered ERP in correct sentences alone in an ANOVA with CLOZE PROBABILITY and GROUP as factors. This analysis revealed a main effect of CLOZE PROBABILITY ($F(1,24) = 8.87$, $p = .007$, $\eta_p^2 = .27$) caused by larger responses for high than low CP sentences (M±SD µV vs. M±SD µV, respectively). However, no significant interaction between CLOZE PROBABILITY and GROUP emerged ($F(1,24) = 0.19$, $p < .67$). This indicates comparable lexical-semantic expectancy in the two groups.

5.3.4 – Further analysis

Following the same structure of the analysis made on the primary investigated components (N400 and P600), we also took into consideration other typically investigated components. Specifically, we tested both the LAN (left anterior negativity) and two separate time windows of the P600: an early time window between 500 and 700 ms and a later one that went from 700 to 900 ms. On the semantic side, we tested the late positive component (LPC) following the N400 that some authors have found in similar experiments (i.e. Hänel-Faulhaber et al., 2014).

5.3.4.1 – Further analysis: LPC

Starting from the latter, we investigated the time window between 500 and 900 ms. along the central line of the scalp. The repeated measures ANOVA revealed an interaction between GROUP and LONGITUDE ($F(1.36, 32.61) = 4.26$, $p = .036$, $\eta_p^2 = .15$).

However, a visual inspection of the curves revealed that this effect could be carried by the previous N400 effect which was stronger in CI users. We can see in Figure 5.13 how the stronger difference between the correct and the violated condition in CI users extends in the tested time window arriving at baseline at around 700 ms. On the contrary, NH controls showed a sharper N400 effect that ended at around 500 ms. Furthermore, the only case in which we see the violated condition to be more positive is in the posterior cluster of electrodes in the NH controls. Overall, we did not find a positivity that follows the N400 in neither CI users nor NH controls.

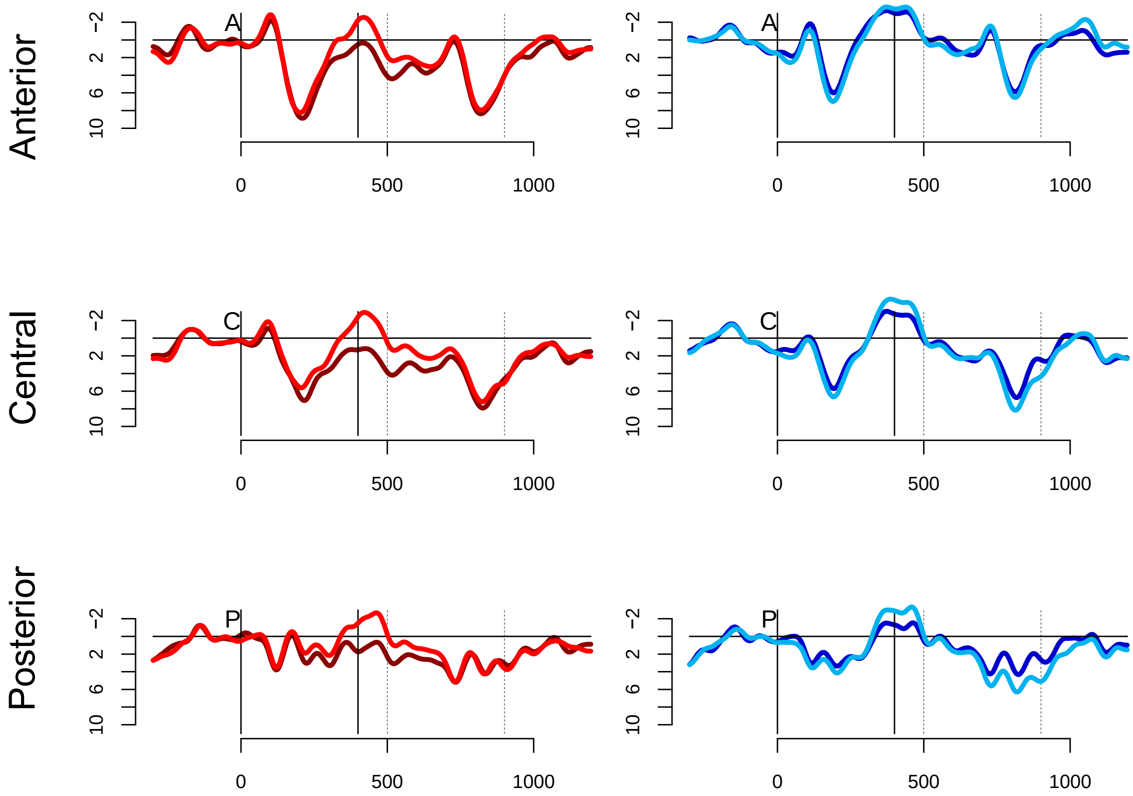

Figure 5.13 – *Grand-average of the waveforms as in Figure 5.10 with the time window of interest between 500 and 900 ms marked by the two dotted vertical lines.*

5.3.4.2 – Further analysis: early P600

As previously mentioned, we divided the P600 time window in two smaller time ranges. We have seen in the introduction that the P600 should not be considered as a monolith; hence, we wanted to see whether the P600 could have any difference between the first and the second half. Starting from the early time window of the P600, we entered the data in a repeated measures ANOVA and as we would have expected, we found a main effect of CORRECTNESS ($F(1, 24) = 5.00$, $p = .035$, $\eta_p^2 = .17$) as well as the main effect of LONGITUDE ($F(1.40, 33.66) = 8.85$, $p = .002$, $\eta_p^2 = .27$). Interestingly, we also found a strong interaction between GROUP, LONGITUDE and CORRECTNESS ($F(1.17, 28.06) = 5.34$, $p = .024$, $\eta_p^2 = .18$). A visual inspection of the waveforms seems to suggest that the difference between the correct and the wrong condition in the early stage of the P600 is stronger in CI users, especially in the anterior and central pools of channels (see Figure 5.14).

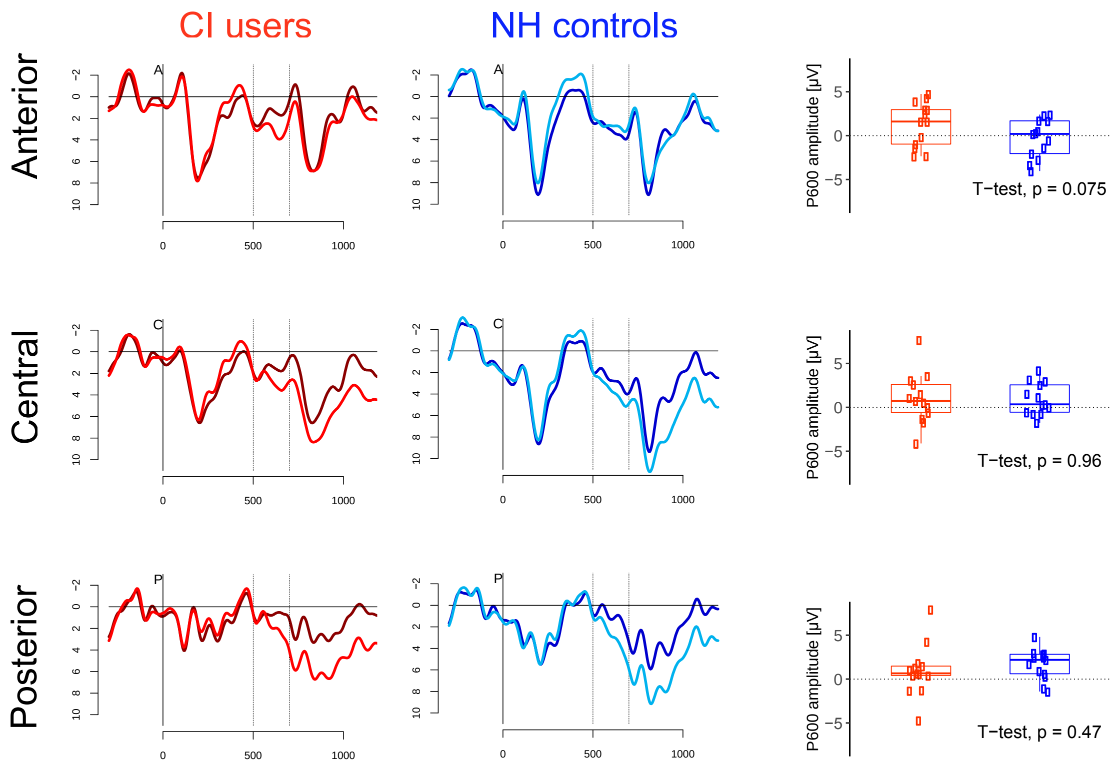

Figure 5.14 – *Grand-average of the waveforms as in Figure 5.10 with the time window of interest between 500 and 700 ms marked by the two dotted vertical lines (on the left).*

5.3.4.3 – Further analysis: late P600

The same analysis was run for the late part of the P600 between 700 and 900 ms. The repeated measures ANOVA revealed the same main effects found for the early stage of the P600. Specifically, a main effect of CORRECTNESS (F(1, 24) = 21.14, p < .001, η_p^2 = .47) and the main effect of LONGITUDE (F(1.40, 33.64) = 5.00, p = .022, η_p^2 = .17). For the late P600, we also found the interaction between CORRECTNESS and LONGITUDE to be significant (F(1.13, 27.23) = 19.18, p < .001, η_p^2 = .44) Contrary to the early time window of the P600, no significant interaction was found with group as factor (all F-values < 1.34) (see Figure 5.15).

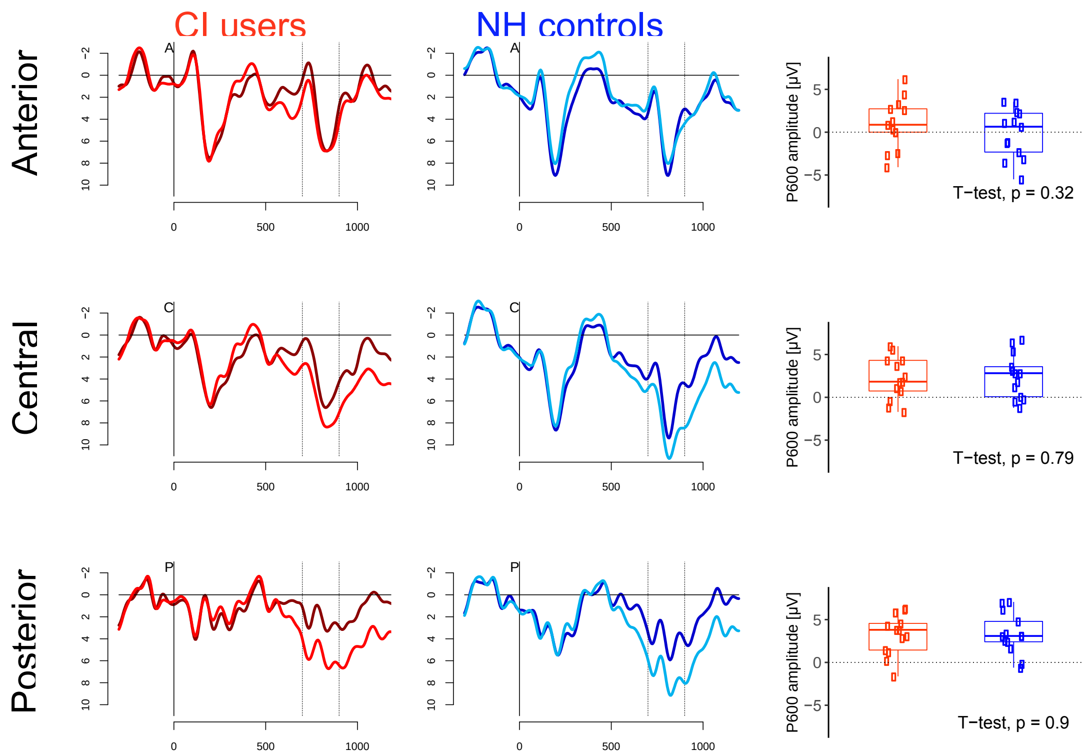

Figure 5.15 – Grand-average of the waveforms as in Figure 5.10 with the time window of interest between 700 and 900 ms marked by the two dotted vertical lines (on the left).

5.3.4.4 – Further analysis: LAN

No main effects or significant interaction were found when the LAN was analyzed with the only main effect of correctness barely missing the significance level (F(1, 24) = 4.08, p = .055, η_p^2 = .15). The absence of an interaction between the two groups revealed that also for the LAN time window, no differences between groups were discovered confirming the similarities between CI users and NH controls' neural signature for syntactic processing.

In order to test the left anterior negativity (LAN) we shifted the analyses from the central line to the lateral lines. We ran the repeated measures ANOVA on the left and right lines that includes three clusters of electrodes each similarly to the scheme adopted for the central line. Specifically, the three clusters of the left hemisphere were the following: Left-Anterior (channels: Fp1, AF3, AF7, F3, F5, F7); Left-Central (channels: FC3, FC5, FC7, C3, C5, C7); Left-Posterior (channels: CP3, CP5, TP7, P3, P5, P7) The three cluster on the right side were: Right-Anterior (channels: Fp2, AF4, AF8, F4, F6, F8); Right-Central (channels: FC4, FC6, FC8, C4, C6, C8); and finally Right-Posterior (channels: CP4, CP6, TP8, P4, P6, P8). The ANOVA used in the analyses had CORRECTNESS (correct or violated), LONGITUDE (frontal, central and posterior) and LATERALIZATION (left, right) as within-participants variables, and GROUP as between-participant variable. The ANOVA revealed only an interaction between LONGITUDE and LATERALIZATION (F(1.30, 31.26) = 5.19, p = .022, η_p^2 = .18) but no interaction neither with GROUP nor with CORRECTNESS.

5.3.5 – Single subject reliability

One of the key features and points of strength of our experiment is the increase of the employed items per condition. With eighty sentences per condition, for a total number of 320 sentences, we aimed to reliably measure the main ERPs of interest at single subject. Given the large individual variability that typically characterize the implanted population, being able to look at individual data, especially for EEG data, is an important step forward. We separately measured single subject data for the semantic and the syntactic conditions. For each participant, we extracted the mean value of the correct and the violated condition in the time windows for the N400 and the P600 from Cz and Pz respectively. Afterwards, we calculated the N400 and the P600 effects as we did in the group analyses. We also took into consideration the average number of epochs that were analyzed after the preprocessing for each single participant and we plotted the results highlighting subjects where the N400 and the P600 effect is considered to be reliable at single subject level (see Figure 3.16 a/b).

In the N400 analysis we can see that, although most of the points are above zero, meaning that the effect is qualitatively present, only two NH participants showed single subject statistical reliability; five CI users showed this statistical significance. This result is in line with the observation of the N400 which resulted to be weaker in NH controls possibly due to cloze probability effects (see Paragraph 5.3.3).

More encouraging is the single subject analysis of the P600 where both CI users and NH controls showed a strong effect and reliability also at individual level (see Figure 5.16 B). This result can give us the flexibility to analyze these subjects in smaller groups when necessary, but even more important, it confirms that the P600 effect that we found at group level is shared by the majority of participants both in CI users and controls.

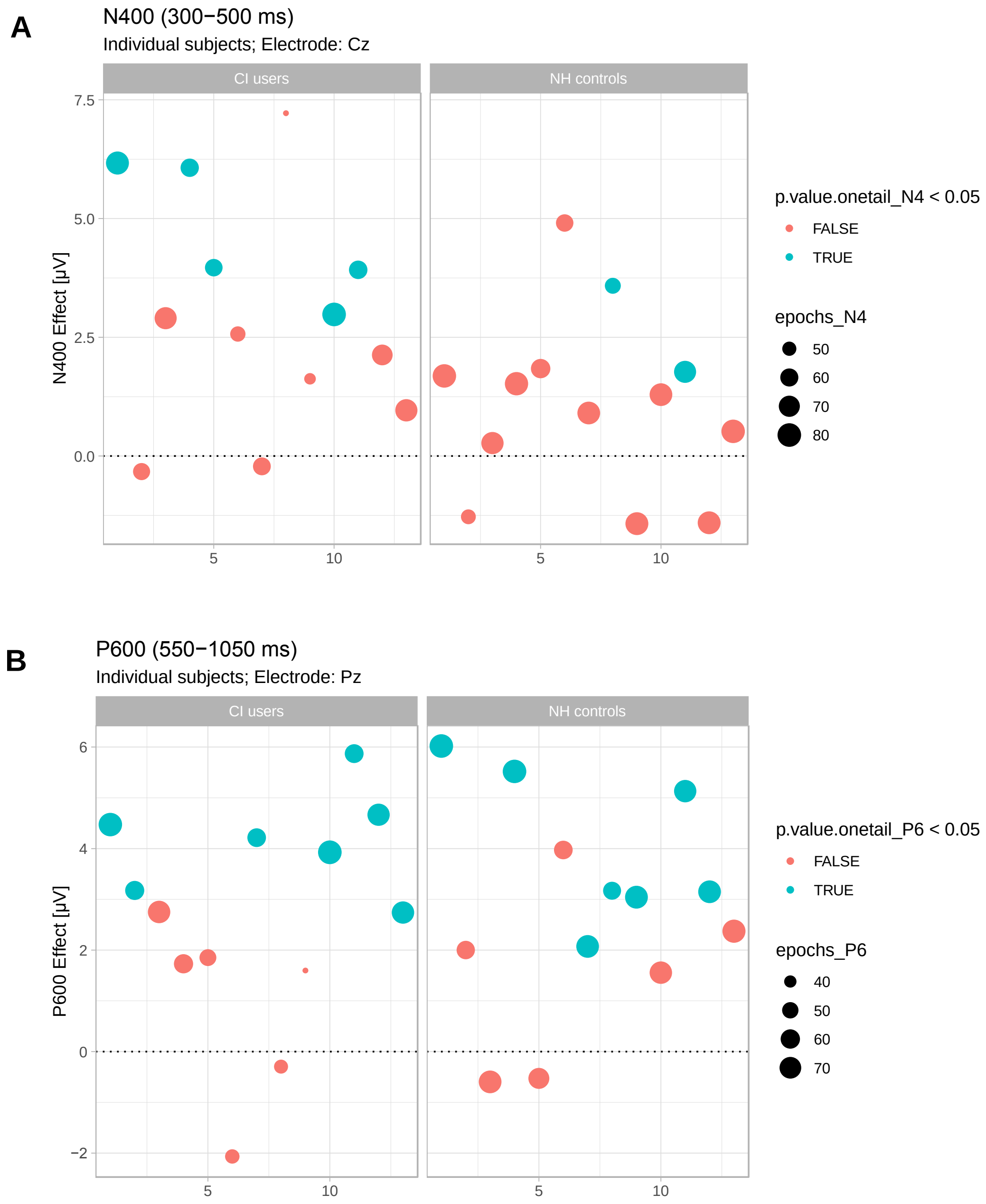

Figure 5.16 – *The plot represents the statistical significance of each participant's N400 (**A**) P600 (**B**) effect. The two colors represent the one tail p-value where the blue indicates that the p-value is below 0.05 and red for p-values above 0.05. The size of the points represents the number of epochs that are considered in this analysis.*

5.3.6 – Correlations

Finally, we aimed to see whether there was a correlation between the age at first implantation and the performance at the acceptability judgements at the end of the sentences (d' index). To this aim we run two separate correlations to test this hypothesis for both the semantic and the syntactic condition. For both semantic (Kendal's rank correlation, tau = -0.46, p = 0.04) and syntactic (Kendal's rank correlation, tau = -0.49, p = 0.03) sentences, the results suggest a decrease of the performance with the increase of the age at first implantation (see Figure 5.17).

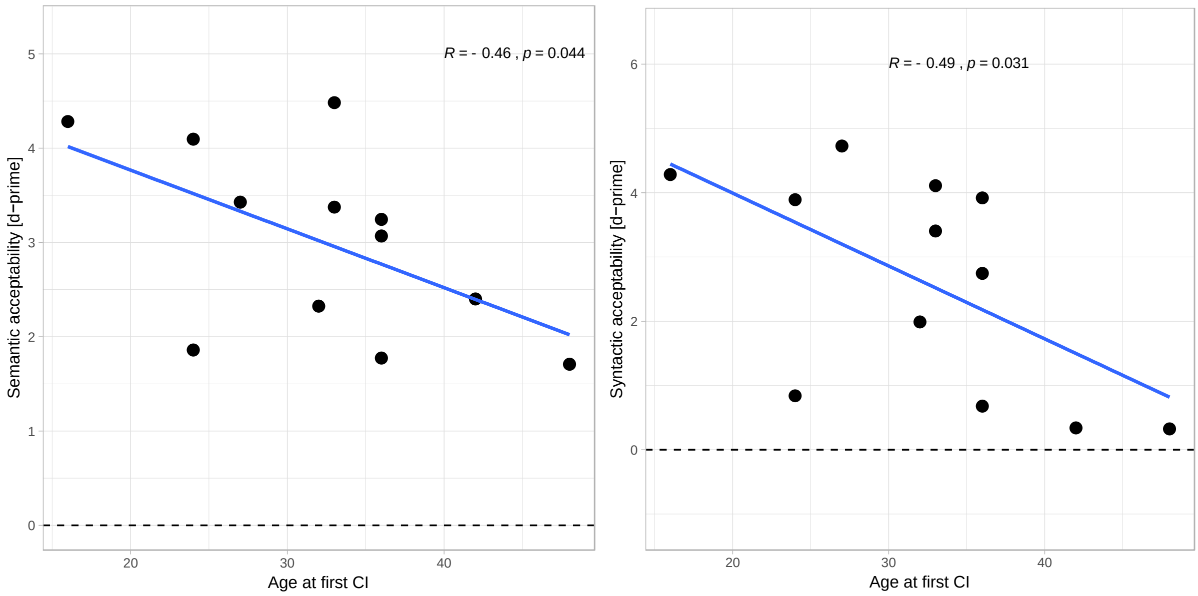

Figure 5.17 - *Kendal's rank correlation between the d-prime index in the acceptability judgement at the end of sentences during EEG and the age at first implant represented in months (left) and Kendal's rank correlation between the d-prime index in the syntactic acceptability judgement at the end of sentences during EEG and the age at first implant in months (right). In this analysis 12 out of 13 subjects were analyzed because we excluded the subject with an age at 1st implantation of 96 months who would have represented an outlier in our distribution. However, analyses including that participant also revealed the same significant effect showed in the two plots.*

No significant correlation was detected when we run correlations between d-prime index of the end of sentences acceptability judgements and the age of deafness onset.

Moreover, we aimed to understand whether the N400 and the P600 amplitudes correlate with the age at first implantation. For the semantic condition, no significant correlation was found, but for the syntactic condition, a correlation between the P600 effect (μV) and the age at first implantation emerged (Kendal's rank correlation tau, tau = -0.46, p = 0.04) (see Figure 3.18)

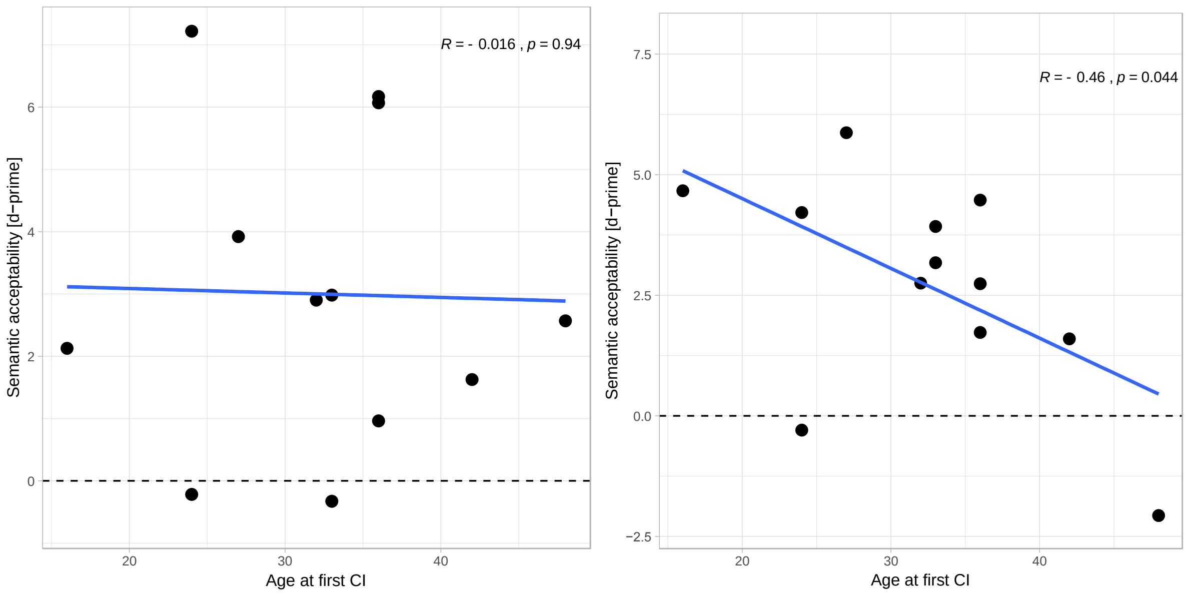

Figure 5.18 - *Kendal's rank correlations between the N400 amplitude (μV) and the age at first implant represented in months (left) and Kendal's rank correlation between the P600 amplitude (μV) and the age at first implant in months (right). 12 out of 13 subjects were analyzed because we excluded the subject with an age at 1st implantation of 96 months who would have represented an outlier in our distribution. However, analyses including that participant also revealed the same significant effect showed in the two plots.*

We also tried several Kendall's Ranking Correlations (see Figure 5.19), where we correlated the age at 1st implant, the time of CI usage and the age of every single implanted participant with each behavioral test that we conducted including the end-of-sentence acceptability judgement task during the EEG experiment (expressed as a d' index). Given the vulnerability of these correlations to be affected by concurrent variables such as age and education, we ran Partial Kendal's Ranking Correlations to double check the validity of the aforementioned correlations. Moreover, we also tried to exploratively correlate the same behavioral tasks with both the N400 and the P600 effects expressed as the difference between the violated and the correct condition in a time window that is the same used in the ERP results. Similarly to the correlations above depicted (see Figures 5.17 and 5.18) we excluded one subject from the analyses because of its distinct age at first implantation, which is much higher if compared to the remaining sample. However, it should be noted that analyses were also conducted with the entire group and results were comparable with a few exceptions that can be easily consulted in Figures 5.19 and 5.20 below. Interestingly, there is a positive correlation between the N400 effect and the semantic fluency task (Kendall's tau = 0.48, $p = 0.03$) as well as two positive correlations between the P600 effect and two syntactic-oriented behavioral tasks: the grammaticality judgement task (Kendall's tau = 0.59, $p = 0.03$) and the end of sentence acceptability judgement task (Kendall's tau = 0.82, $p < 0.01$). All these three results corroborate the validity of our tasks that even with such a small number of subjects have been able to prove the sensitivity to the linguistic features for which were thought and built in the first place. This assertion is based on the assumption that the N400 and the P600 are linked respectively to semantic and syntactic linguistic features.

5.4 – General discussion

We started this study with the aim to test whether cochlear implantation in a prelingually deaf group would have impacted typical neural signatures of semantic and syntactic written sentence processing. We collected EEG data during a reading task from thirteen prelingually deaf CI users that were matched with an equal number of similarly aged hearing controls. Sentences were either semantically or syntactically violated aiming to test typical ERPs of language processing: N400 and P600 respectively. We also run correlations between the amplitude of those components and behavioral measures as well as individual information. Finally, we tested single-subject reliability of the effect of the main components.

5.4.1 – LAN, P600 and the syntactic processing

When we analyzed the results of the syntactic condition, we expected to find a smaller P600 effect in response to syntactic violations as reported by some studies in deaf non-implanted participants (Mehravari et al., 2017) but also in implanted postlingually deaf individuals (Hahne et al., 2012). Although these experiments tested different groups, together with behavioral results that indicate the overall weakness in the syntactic skills of prelingually deaf children, we expected to find a modulation of the P600, especially if combined with weaker performances in the syntactic behavioral measures. However, at group level we did not find any difference in the overall P600 time window analysis with the CI users' group showing a statistically comparable P600 effect in response to our syntactic agreement violations. Accordingly, also the left anterior negativity (LAN) resulted to be statistically not different between the two samples. The two groups seem to be responding at violations in similar ways, overall.

Yet, we also detected differences between CI users and NH controls. Specifically, we found differences in the early time window of the P600 where CI users showed a stronger effect in the frontal sites, possibly revealing differences in the early stages of the syntactic integration process underlying the P600. Furthermore, and most interestingly, in the group of CI users, the amplitude of the P600 effect is predicted by the age at cochlear implant activation. Specifically, we found a correlation showing that the magnitude of the P600 effect progressively decreases as age at implantation increases. This result suggests that the restoration of the typical neural signature of syntax processing (P600) during a reading task may depend on the timing when the CI is made, with a further indication that early implantation can lead to results that are more comparable to normal-hearing participants.

When considering this novel piece of evidence emerging from our work, it should be noted that with the exception of one participant, all the other CI users were early CI adopters (i.e., CI activation by 4 years of age). Therefore, although all of our CI participants had a diagnosis of profound deafness, but at the same time were stimulated through the CI early and substantially during their development. All of our participants reported to extensively use the CI throughout the entire day (all participants reported to always use their CI(s), while awake), with an overall good level of proficiency. This characteristic of our sample has to do with the selection made during the recruitment where we only choose people with a good CI outcome (based on the judgement of clinicians that helped during the recruitment process). In support of our findings, single subject analyses proved the reliability of our paradigm by showing statistically significant P600 effect in the majority of our CI users as well as for our controls which served even more as a validation for our experiment given that the P600 was strongly expected in normal hearing controls.

These results are particularly interesting when compared to results in the literature where the P600 wasn't found in deaf individuals without CI where they supported *"the idea that non-native signing deaf adults likely process written language differently than deaf native signers and hearing adults"*. (Mehravari et al., 2017).

5.4.2 – N400 and the semantic processing

We expected comparable results for semantic components during our EEG task. Specifically, we were looking for comparable N400 effects in response to semantic violations embedded in our written sentences. This prediction was based on the literature that showed good semantic knowledge in deaf CI users. Especially, given the relatively high linguistic proficiency of our CI participants and given the preference for content words showed in the existing literature by hearing impaired people. All of our semantic violations occurred on content words indeed. We found comparable semantic ERP components (N400) in response to meaning incongruities in both groups. Interestingly, the N400 effect in deaf implanted people was actually statistically stronger compared to normal-hearing controls and its amplitude wasn't predicted by the age at implantation, unlike the P600. This result could suggest that stronger semantic strategies in sentence processing may be at play in CI users, although cloze probability results provide more information that helped us in the interpretation of this unexpected result. Specifically, the stronger N400 that we found in CI users could be explained by the fact that the effect of correctness was present for both high and low cloze probability sentences whereas in controls, only high cloze probability sentences showed a difference between the correct and the violated condition.

5.4.3 – Behavioral measures

Behavioral measures confirmed that, even after cochlear implantation, linguistic difficulties remained in our sample of deaf CI users confirming previous results in the literature. These issues seem also to be stronger with the increase of the age at implantation again highlighting the importance of an early surgery in children with preverbal deafness onset or congenital deafness. Overall, our participant in the CI group performed statistically worse than their age peers. CI users produced less words during the semantic fluency task and they required more time while performing worse during the lexical decision task. These two tasks were part of the lexical-semantic cluster of behavioral tasks. Therefore, behavioral measures do not directly support the hypothesis of a stronger semantic strategy adopted by CI users. In fact, weaker performances in these tasks suggest that the semantic access is still slightly impaired even though the N400 effect resulted to be higher in the clinical group.

5.4.4 – Summary, limitations and future steps

In summary, these results seem to suggest that early cochlear implantation can promote comparable brain activations in response to syntactic violations in both early deaf and hearing adults. Despite slightly but significantly worse performances in the behavioral tasks, CI users showed a surprisingly good achievement in both the semantic and even more importantly, in the syntactic domain.

As we previously discussed both in the introduction and in the methods section, our project introduced some methodological innovations that allowed us to obtain strong results both at group and also to some extent at single subject level. By doubling the usual number of stimuli employed in similar experiments and by carefully build the stimuli, we have been able to efficiently detect the ERP components that we aimed to observe. Furthermore, our results brought useful information both for the clinical and the psycholinguistic communities. Specifically, not only we corroborated once more well-known ERP components in the control group for the Italian language, but we also hopefully produced interesting data for clinicians and speech therapists.

Of course, by dealing with such a delicate and multifaceted population, there are some flaws and limitation that we are aware of. For example, some of the CI users showed a weaker P600 effect, but that could be related to a less efficacy of the CI. If this would be the case, we could argue that instead of a problem related to the critical period for language acquisition, it could be more likely linked to a problem in the development of acoustic skills during that sensitive period. Furthermore, it should be noted that, because of the requirements of the ERP technique, we have been able to employ only one type of violation during the EEG task. That prevented us to test different syntactic agreement violations as well as other syntactic and semantic manipulations as well. Behavioral measures like the sentence picture matching task for example, revealed a higher complexity in the syntactic processing in the group of prelingually deaf CI users. Further investigations should go in the direction of better investigate more linguistic features and manipulations, especially in the syntactic field. Moreover, future investigations should be made with natural text instead of standalone sentences showed one word at a time in order to make the experiment more natural and similar to the everyday experience where rarely we listen or read single and de-contextualized sentences.

6.0 – Written sentence processing in postverbal CI users

6.1 – Introduction

A consistent proportion of CI users did not become deaf early in life. In fact, cochlear implant is also a widespread clinical approach with people who became deaf later in life or simply after language acquisition. Specifically, not only for those who lost hearing a few years after the age of 3.5 – 4 yrs. but also for individuals that became deaf at up to 50 years old after many years of natural hearing. When we consider participants in this specific group, we deal with people that, to some extent (some much more than others) have had experience with natural hearing and therefore they acquired and processed linguistic information in a way that is comparable with the hearing group. A few studies in the literature compared postlingually deaf CI users and age-matched hearing controls with a reading task while recording EEG. Among them, we already presented in the general introduction the study by Hahne and colleagues (2012) which represents a crucial work to be repeated here as well.

Hahne and colleagues (2012) aimed to better understand whether the cognitive mechanisms of sentence processing in late deaf CI users were impacted by cochlear implantation. By investigating this population, any difference that would have been found, would have suggested an interference of the CI, in processes that were already consolidated in this late deaf population. They collected data from thirteen German postlingually deaf adults (mean age 51 years) and they compared them with an equal number of control participants. They asked subjects to listen to a set of sentences presented via speakers. Sentences were divided in 4 types: correct sentences with high cloze-probability, correct sentences with low cloze probability, incorrect sentences with selectional restriction violation and incorrect sentences with argument structure violation (for further details, see Hahne et al., 2012). Overall, they found the N400 effect in response to all sentences. Interestingly, CI users showed a stronger late positivity across conditions possibly reflecting a stronger revision process in response to violation (Friederici, 2002; Kaan et al., 2000). They also found that the P600 effect expected for the argument structure violation was present only in the control group. Therefore, they concluded that the degraded sound delivered by cochlear implant can have an impact on language comprehension even canceling specific neural signatures with the syntactic one being more susceptible.

If we do expect that the integrity of language acquisition process is responsible for the development of typical neural signatures of language such as the N400 and the P600, we should expect little-to-no differences between ERPs recorded in the postverbal deaf population and its control group. However, other variables such as duration of deafness and duration of cochlear implant use, should also be taken into account. The notion that reiterated experience with the CI can alter sentence processing mechanisms even when linguistic materials are delivered through an intact sensory system (vision) may be akin to the notion of ‘attrition’, a phenomenon studied in the context of bilingualism. The language experience after cochlear implantation is diverse for phonology due to the difference in the way CI users perceive and process their own native language. Attrition has been defined as a non-pathological change or loss in the abilities in L1 after being exposed for a prolonged time to another language (Schmid & Köpke, 2004). Although this concept has been usually linked to fully functional L2 learners who already had a first language from birth, we cannot exclude to be able to find some effect in relation to the age at deafness onset and more likely with the duration of the experience with cochlear implant. If the quality of the delivered auditory signal is in fact so much degraded or different from natural perceived language, we could hypothesize that even within the same language, late deaf CI users have to re-learn to process some part of the speech possibly by implementing different strategies of parsing and interpretation of sentence structure. This could also have as a consequence an impact on written language processing.

An experiment with written stimuli, similar to the one discussed in this thesis, that address the impact of attrition on sentence processing has been conducted on Italian L1 individuals who emigrated in English-speaking environment in Canada in the adulthood, termed 'Italian attriters' (Kasparian, Vespignani, & Steinhauer, 2017). Specifically, the authors compared 24 Italian attriters with 30 Italian controls living in Italy. They used number-agreement violations between subject and verb. Number was further manipulated in a following adjective that structurally need to refer to the subject. Despite they did not find any relevant difference in the behavioral measures, they showed group differences in the amplitude, scalp distribution and duration of the LAN/N400 + P600 effects. Specifically, they found differences in the posterior P600 in response to number-agreement violations with controls showing a longer lasting positivity, being possibly engaged in more extensive integration processes compared to Attriters. Furthermore, Attriters also showed longer reaction times in the acceptability judgement at the end of the sentences which supports the idea of non-Attriters to be faster in the overall online processing. One of the take home messages of this work in relation to our study, is that neural signatures (ERP components) of an L1 can be modified throughout the lifespan. In the case of the study of Kasparian and collaborators, these modifications were likely to be triggered by the mechanism of attrition; in our study, we can expect differences to be triggered by the difference of the listening experience provided by cochlear implant.

Though, it should be noted that language in this case is the same with the difference residing in the hearing quality experience. Therefore, if it is true that there is an impact of phonological features on written stimuli in postlingually CI users, we could expect to see a modulation of the P600 or a shift of toward a semantic strategy like in the preverbal group with stronger N400 or N400-like responses to syntactic violations. We can predict that the altered and deteriorated acoustic information delivered by the CI could have an impact in the role of semantic elements within the sentences. They could become more salient by being more easily perceived through the implant arising as a consequence, a stronger N400 component when the expectation is violated.

6.2 – Methods

Procedures, EEG preprocessing and analyses followed the same structure and principles of the previous studies (see Chapter 3). Whenever differences occur, it will be thoroughly specified.

6.2.1 – Participants

Twenty participants took part in the study (see Table 6.1). Ten were late-deaf with monolateral or bilateral cochlear implant (CI). With the cochlear implant switched off, all deaf participants had a diagnosed bilateral profound deafness with no usable residual hearing. All participants (5 female; mean age = 46.8 years, age range: 20 – 66) passed all the EEG preprocessing steps (see §) retaining on average more than 95 % of the epochs (96 % of epochs in the semantic condition; 95 % of epochs in the syntactic condition). None of participants reported any neurological problems and all of them had normal or corrected-to-normal vision. All participants were at over eighteen years old therefore, they all underwent the same procedure and contrary to participants of study one, the all were tested in the same laboratory with the same equipment. None of them have had experience with sign language. All participants fulfilled an anamnestic form as in study one.

It should be mentioned that our participants have been accurately selected from clinicians to fulfill our basic requirements to complete the tasks. We are aware of participants who refused or were not contacted because they did not fulfill our requirements even within the late deafness onset group.

ID	*Sex*	*Education (yrs.)*	*Age (yrs.)*	*Deafness onset (years)*	*Use of CI (months)*	*N. of CIs*	*Age at CI (years)*	*Hearing aids*
*CI-post-1**	F	13	63	35	36	2	60	Y
*CI-post-2**	M	8	50	30	84	2	43	N
CI-post-3	M	13	20	5	168	2	6	Y
CI-post-4	M	18	33	32	12	1	32	Y
CI-post-5	F	8	66	52	84	2	59	Y
CI-post-6	F	10	56	34	60	2	51	Y
CI-post-7	F	10	23	11	144	2	11	N
CI-post-8	F	13	68	10	36	2	65	Y
*CI-post-9**	M	18	41	40	12	2	40	Y
*CI-post-10**	M	11	48	38	120	1	38	N

Table 6.1 – *Selected information about deaf individuals who voluntarily participated in the study. This information is coming from both the questionnaire they were required to fulfill after the EEG session and from a detailed spreadsheet directly provided by clinicians at the hospital (where applied *).*

10 normal hearing controls (7 females; mean age = 43.9 years, SD = 18.25, age range: 20-65) were selected to match as closer as possible the age of the CI users

included in the study (mean difference between groups = ± 0.9 years, SD = 0.98; p = 0.91). All control participants reported to have normal hearing and had normal or corrected-to-normal vision. None of the hearing subjects were familiar with Sign Language and none of them have had neurological issues in the past. As for Study 1, control group underwent the same procedures as the CI group with the exception of the clinical part of the anamnestic questionnaire.

6.3 – Results

6.3.1 – Behavioral measures

Behavioral measures follow the same scheme and rationale of those present in Chapter 5.

6.3.1.1 – End-of-sentence acceptability judgement

In the acceptability task at the end of each sentence during the EEG task, we did not find any statistically relevant difference between the two groups both in the semantic (Wilcoxon, p = 0.36) and syntactic (Wilcoxon, p = 0.41) condition, with a slightly larger score dispersions for CI users (range: 2.81 – 4.94) compared to controls (range: 3.85 – 5.46) in the syntactic condition (see Figure 6.1).

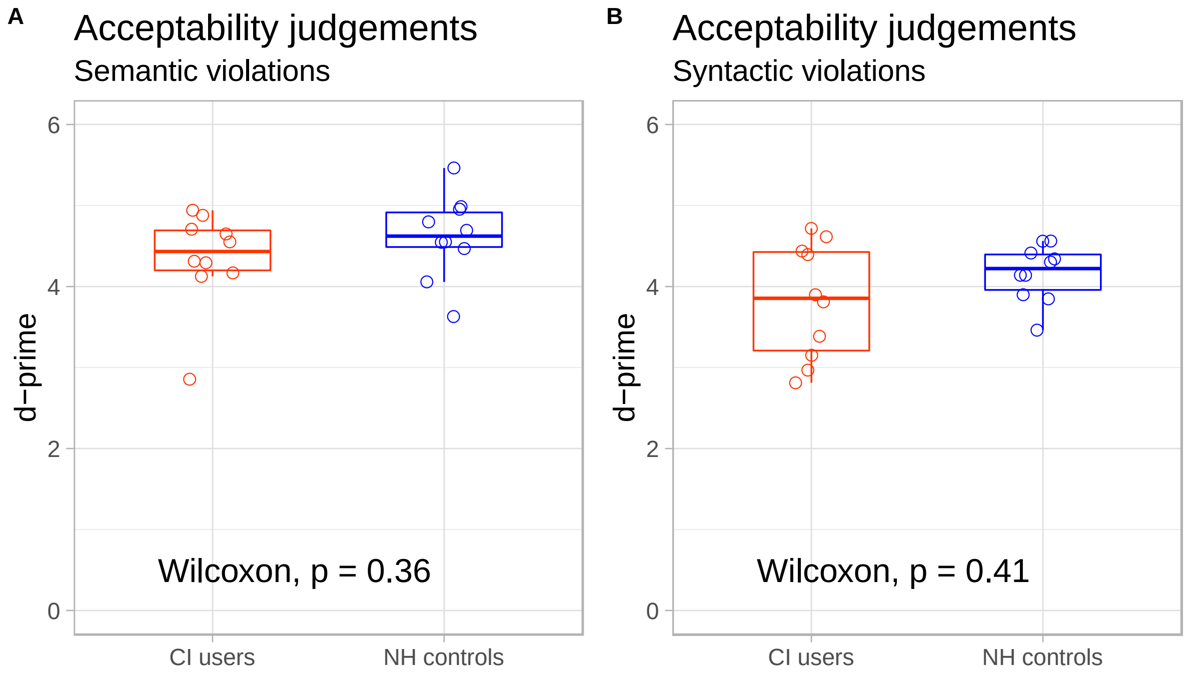

Figure 6.1 – ***A****) d-prime index calculated for CI users (in red) and normal hearing controls (in blue) for the end-of-sentence acceptability judgement task in the semantic condition.* ***B****) d-prime index calculated for CI users (in red) and normal hearing controls (in blue) for the end-of-sentence acceptability judgement task in the syntactic condition.*

6.3.1.2 – Behavioral tests - Semantic set

The lexical decision task revealed no significant difference between CI users and normal hearing controls when we tested the accuracy (Wilcoxon, p = 0.63). However, reaction times were significantly higher for CI users when compared to controls (Wilcoxon, p = 0.024) (see Figure 6.2). This seems to reflect good vocabulary skills while possibly, showing a weaker confidence or slower access to semantic knowledge.

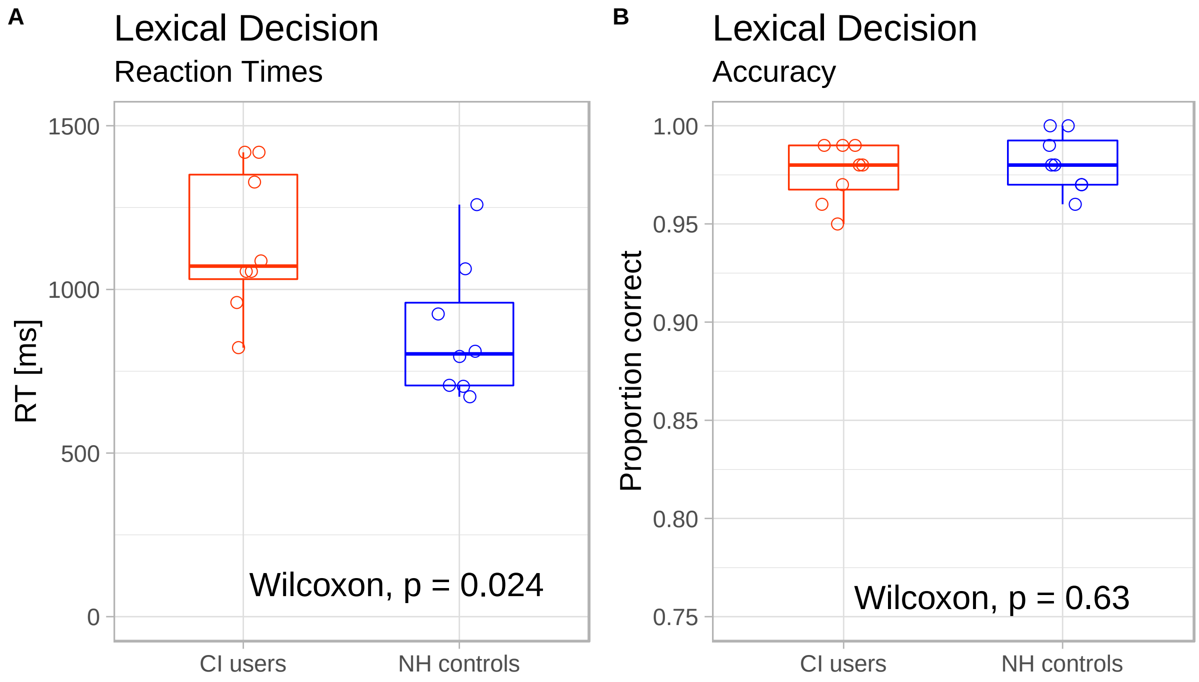

Figure 6.2 – ***A****) Reaction times of CI users (in red) and normal hearing controls (in blue) in the lexical decision task.* ***B****) Proportion of correct responses of CI users (in red) and normal hearing controls (in blue) in the lexical decision task. Both group's accuracy is close to 100% but reaction times are significantly higher for CI users. Data points represent single subject performance.*

In the semantic fluency task, a strong variability between subjects is present in both groups and there is no significant difference between groups (Wilcoxon, p = 0.36) (see Figure 6.3). This result suggests that neither of the two groups performed worse than the other when they had to pronounce as many words that they can after the name of a category appeared on the screen. Contrary to the results revealed by the lexical decision task, here the two populations seem to be comparable for their speed accessing semantic knowledge.

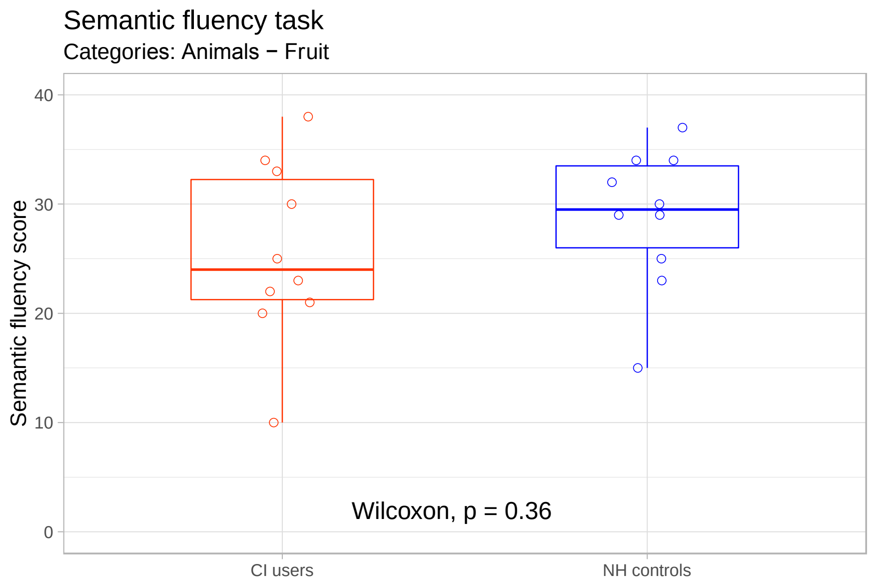

Figure 6.3 – *Total number of pronounced words during the semantic-fluency task. CI users (in red) and normal hearing controls (in blue) did not show any significant difference in the performance. Data points represent single subjects performance.*

6.3.1.3 – Behavioral tests - Syntactic set

We then analyzed the performance in the grammatical accuracy task where participants were asked to judge a set of sentences, half containing several different violations, one per sentence. Although all participants performed very good with none of them below 90% of accuracy, the mean performance of the controls is significantly better than the performance of the CI users (Wilcoxon, p = 0.042) (see Figure 6.4).

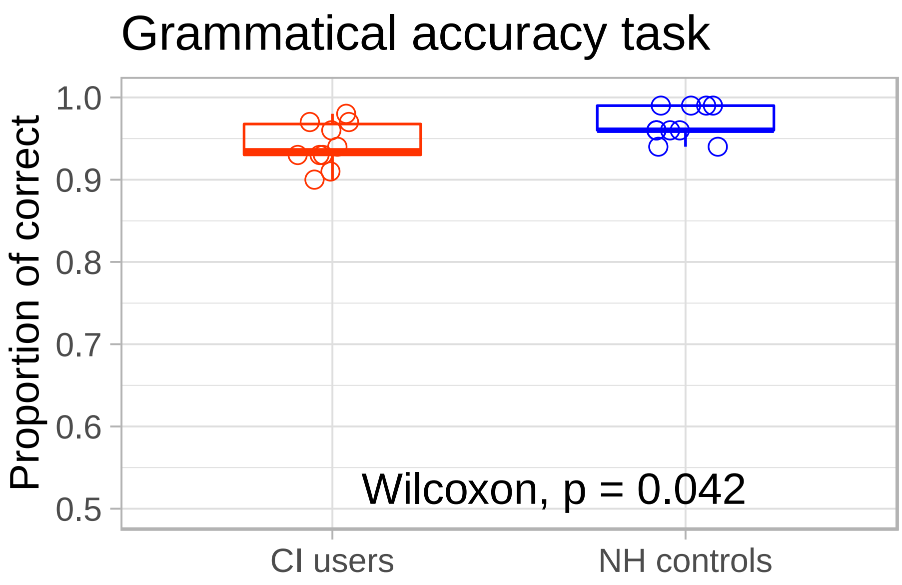

Figure 6.4 – Proportion of sentences that have been correctly judged by CI users (in red) and NH-controls (in blue). The statistical comparison between the two populations revealed a significant difference ($p = 0.042$) with CI users performing slightly worse than hearing controls. Data points represent single subject.

By asking participants to assign one out of four pictures to a sentence with several syntactic structures and complexity manipulations (see Chapter 3.2 for further details) we aimed to better investigate the syntactic skills of our participants. Contrary to the comparison between preverbally deaf CI users and their age-matched hearing controls, none of the comparisons in this task revealed any significant difference between postverbally deaf CI users and normal hearing controls with both groups performing almost always at ceiling in the accuracy measure (see Figure 6.5). As expected, this seems to suggest that the syntax is intact in the postverbal deaf group.

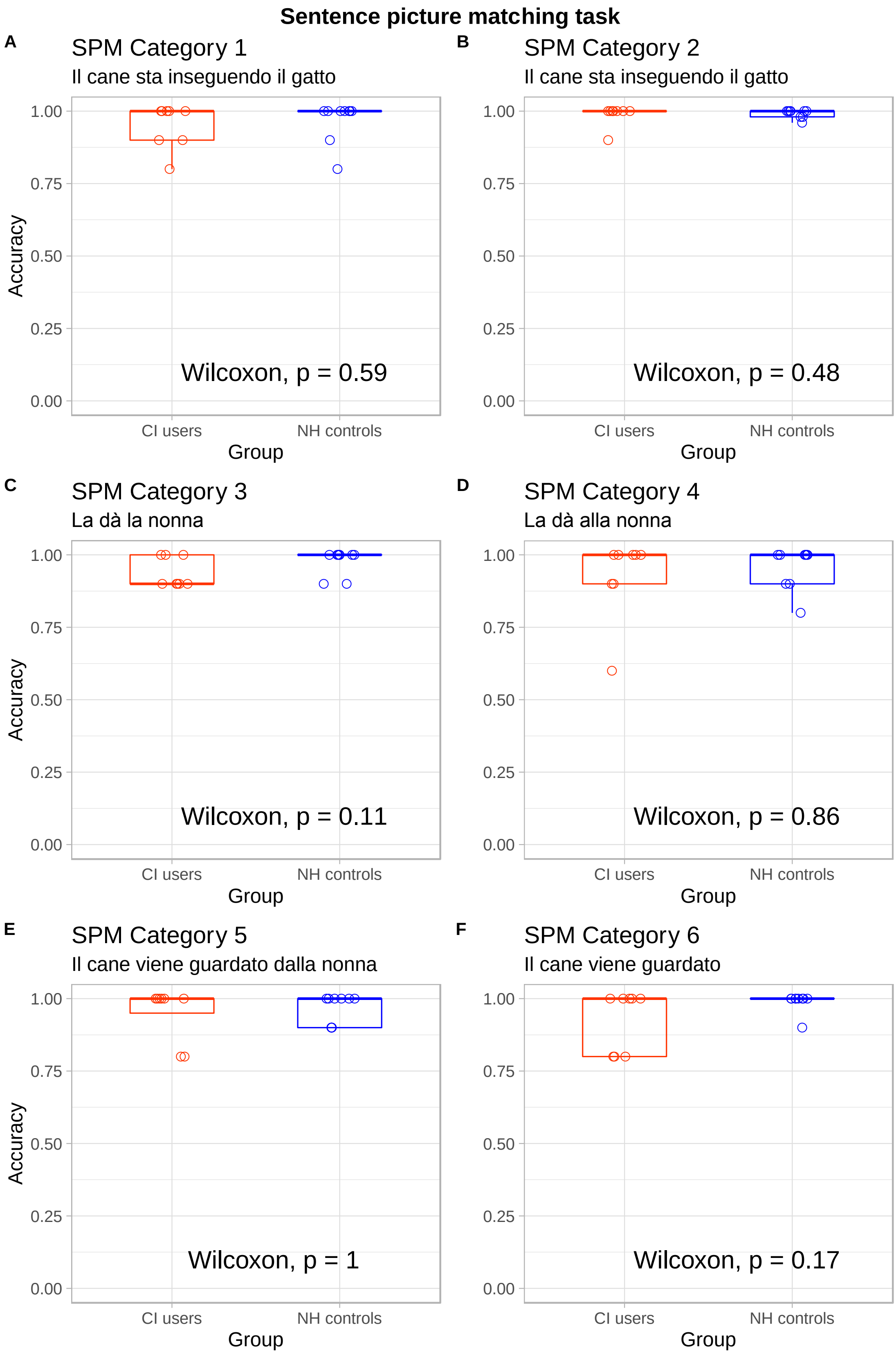

Figure 6.5 – *Accuracy of CI users (in red) and NH-controls (in blue) in the 6 categories from 1 (**A**) to 6 (**F**). Contrary to results from Study 1, no significant difference was found between groups with both performing almost always at ceiling. Data points represent single subject performance.*

The error detection task did not reveal any difference between the two groups for none of the type of error that we inserted in the text (see Figure 6.6). Overall, participants performed rather well with an average of around 80% of the errors detected.

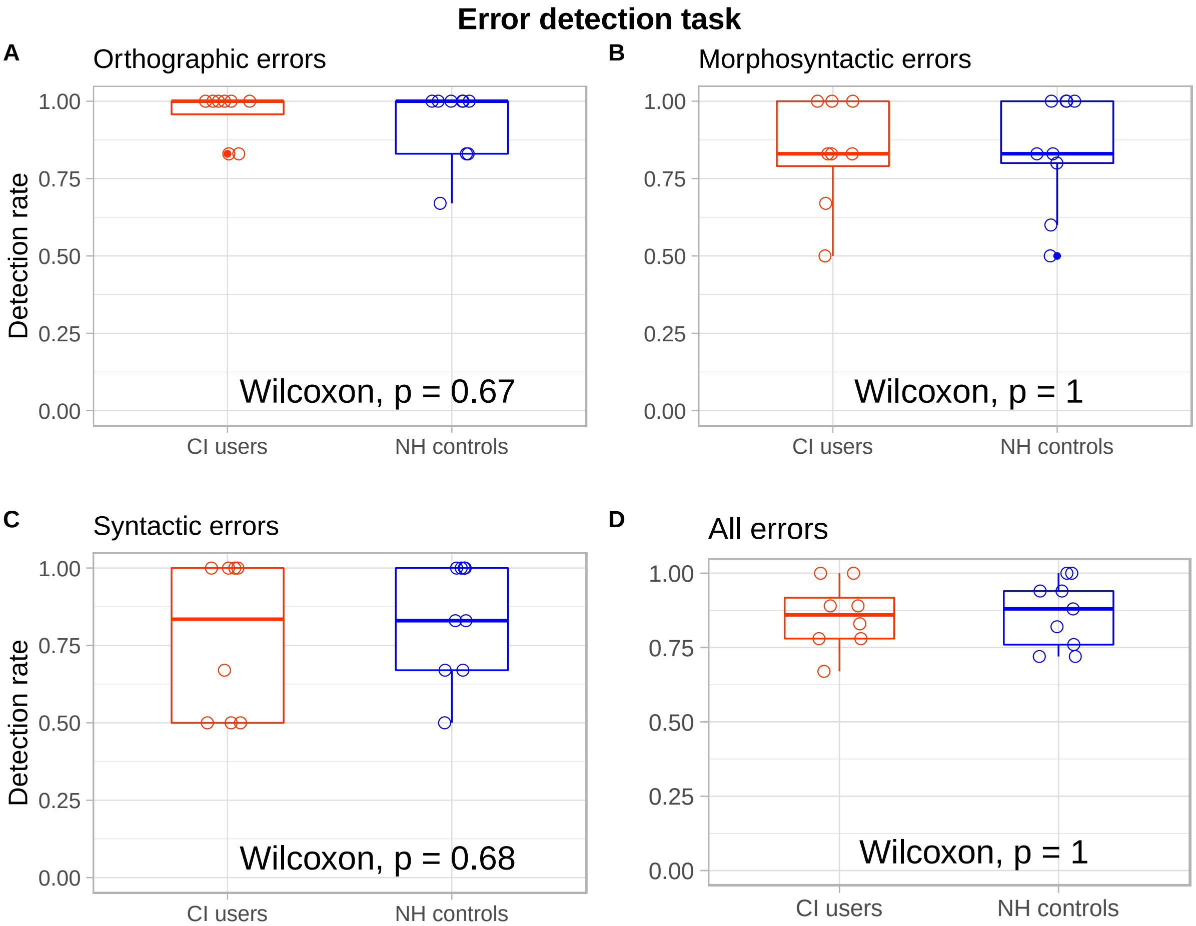

Figure 6.6 – *Proportion of orthographic (**A**), morphosyntactic (**B**), syntactic (**C**) and all (**D**) errors correctly detected by CI users (in red) and normal hearing controls (in blue) in the lexical decision task. Clearly, no significant difference was detected by the task between the two groups. Data points represent single subject performance.*

6.3.2 – ERPs

6.3.2.1 - P600 and the syntactic processing

To compare the P600 component between Postverbal CI users and NH controls, we pooled medial electrodes into three separate clusters (see Figure 6.7 from Study 1), averaging the EEG signal in the same interval of 550-1050 ms.

We entered recorded values in a repeated measures ANOVA with CORRECTNESS (correct or violated) and LONGITUDE (frontal, central and posterior) as within-participants variables, and GROUP as between-participant variable. This analysis revealed a main effect of CORRECTNESS ($F(1, 18) = 44.42$, $p < .001$, $\eta p^2 = .71$), LONGITUDE ($F(1.21, 21.75) = 9.40$, $p = .004$, $\eta p^2 = .34$) and the interaction between CORRECTNESS and LONGITUDE ($F(1.38, 24.90) = 8.33$, $p = .004$, $\eta p^2 = .32$). Critically, no significant main effect or interaction involving the GROUP factor emerged (all F-values < 1.82) (see Figure 6.7). As for the study on the preverbal group, we also divided the P600 in two smaller time windows: early and late P600. Specifically, we used two separate time windows, one between 500 and 700 ms (early P600) and the second between 700 and 900 ms (late P600). We entered the values in a repeated measures ANOVA with the same structure as the previous one. For the early time window of the P600 we unsurprisingly found a main effect of CORRECTNESS ($F(1, 18) = 31.52$, $p < .001$, $\eta_p^2 = .64$) and the main effect of LONGITUDE ($F(1.37, 24.61) = 9.98$, $p = .002$, $\eta_p^2 = .36$). No main effect or interaction involving the GROUP factor emerged (all F-values < 2.47) revealing no differences between the CI users and the NH controls in the early stage of the P600. The same type of results emerged for the late stage of the P600 with the ANOVA only revealing the main effects of correctness ($F(1, 18) = 32.29$, $p < .001$, $\eta_p^2 = .64$) and longitude ($F(1.13, 20.38) = 14.23$, $p < .001$, $\eta_p^2 = .44$) as well as the interaction between correctness and longitude ($F(1.33, 23.90) = 12.06$, $p < .001$, $\eta_p^2 = .40$). Even for the late stage of the P600 we did not find any main effect or interaction involving group as factor (all F-values < 0.66) revealing no differences between CI users and hearing controls in this time window. Overall, we can conclude that the P600 in its entirety is fully comparable between the two investigated groups possibly suggesting a similar processing of syntactic number-agreement violations.

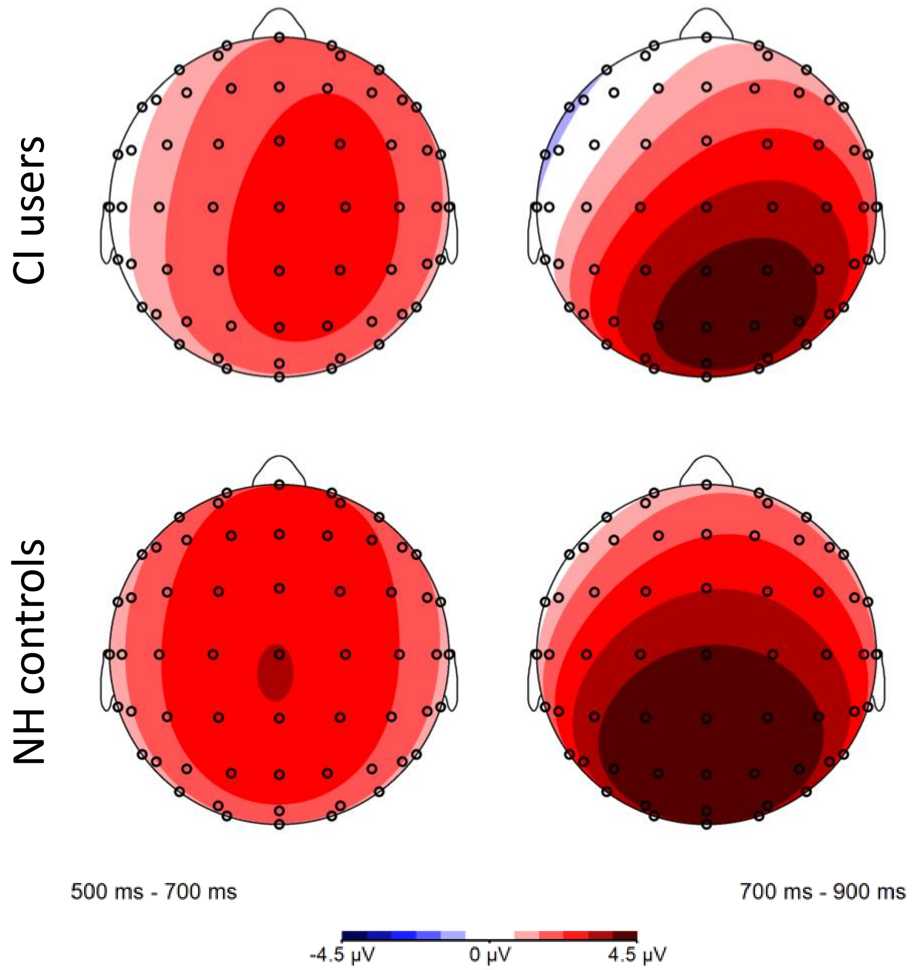

Figure 6.7 A – Averaged topographic distribution of the P600 between 500 – 700 & 700 – 900 ms after the onset of the target word for CI users on the top (N=10) and NH controls on the bottom (N=10). The scale ranges symmetrically from -4.5 to 4.5 µV.

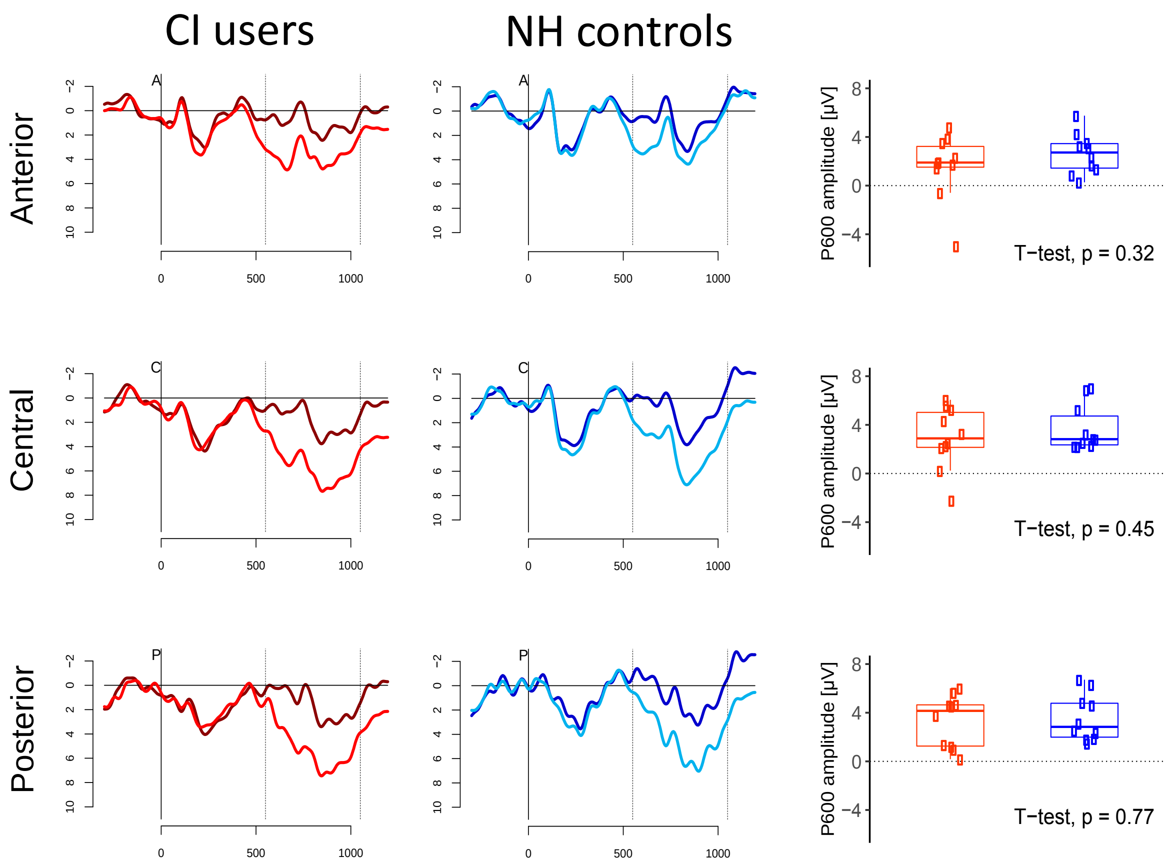

Figure 6.7 B – *Averaged waveforms of the P600 (time window between 550 and 1050 ms) responses (left) after stimulus onset in CI users (in red) and normal hearing controls (in blue) for anterior, central and posterior clusters along the central line. Control sentences are represented by the darker line while sentences that contain a violation are displayed with the lighter line. On the right, t-test comparison between CI users (in red) and controls (in blue) for the P600 amplitude (violated condition minus correct condition) expressed with positive values.*

We also analyzed the left anterior negativity (LAN) time window (300-500 ms) in the left and right hemisphere of the brain using the same method described in the previous study. To test the LAN, we ran an ANOVA that had CORRECTNESS (correct or violated), LONGITUDE (frontal, central and posterior) and LATERALIZATION (left, right) as within-participants variables, and GROUP as between-participant variable. We found a main effect of LONGITUDE (*F(1.21, 21.79) = 7.55, p = .009,* η_p^2 *= .30*) and we also found an interaction between CORRECTNESS and LATERALIZATION ($F(1, 18) = 20.87$, $p < .001$, $\eta_p^2 = .54$) as well as between GROUP, CORRECTNESS and LATERALIZATION (F(1, 18) =

12.70, p = .002, η_p^2 = .41) and CORRECTNESS, LONGITUDE and LATERALIZATION (F(1.45, 26.16) = 5.48, p = .017, η_p^2 = .23) which suggest the existence of the LAN across the two groups of participants although the previous interaction suggested that the lateralization of the LAN differs between groups.

6.3.2.2 – N400 and the semantic processing

Following the same scheme of analyses of Study 1, we entered recorded values in an ANOVA with CORRECTNESS (correct or violated) and LONGITUDE (frontal, central and posterior) as within-participants variables, and GROUP as between-participant variable. This analysis revealed a main effect of CORRECTNESS (F(1, 18) = 21.73, p < .001, ηp^2 = .55) and significant interaction between CORRECTNESS and LONGITUDE (F(1.27, 22.94) = 3.99, p = .049, ηp^2 = .18). Critically, no significant main effect or interaction involving the GROUP factor emerged (all F-values < 2.08). This indicates that the experiment has been able to elicit a difference between the correct and the violated condition as well as some form of localization of the N400 provided by the interaction between correctness and longitude. A visual inspection of the waveforms suggests that the N400 in response to semantic violations for CI users seems to be more frontally distributed compared to NH controls. Although, it is not statistically significant, the T-test revealed a tendency in the anterior pool of channels (p = 0.077) that we speculate, would be probably stronger with a higher number of participants involved.

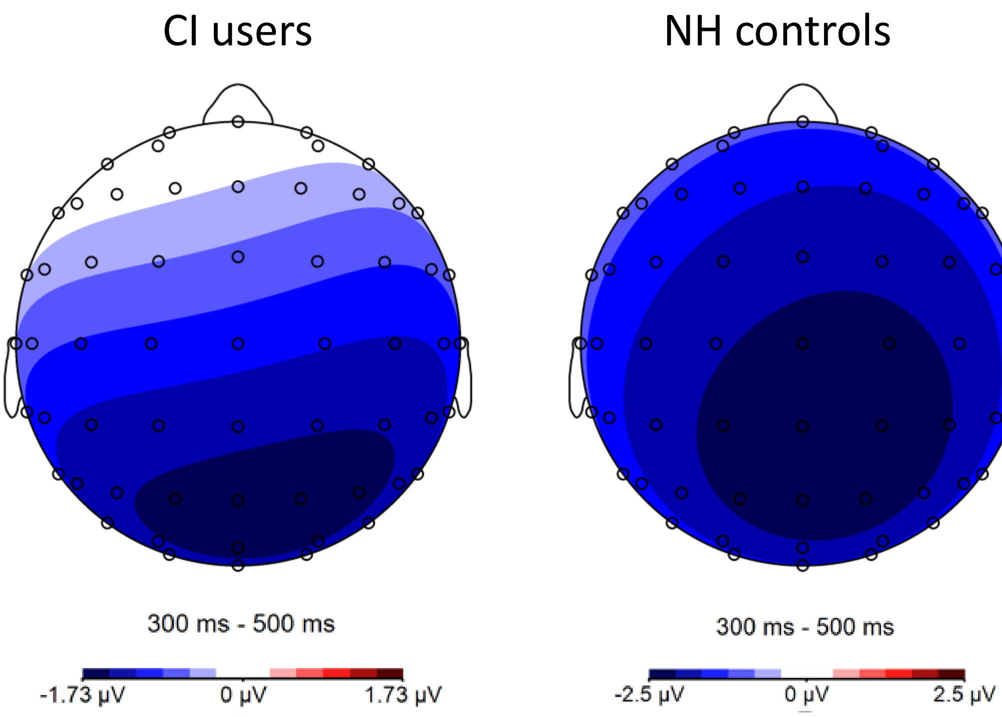

Figure 6.8 A – *Averaged topographic distribution of the N400 between 300 – 500 ms after the onset of the target word for CI users on the left (N=10) and NH controls on the right (N=10). For display purposes, <u>scales are not equal</u> between groups: -1.73 to 1.73 µV for CI users and -2.5 to 2.5 µV for NH controls.*

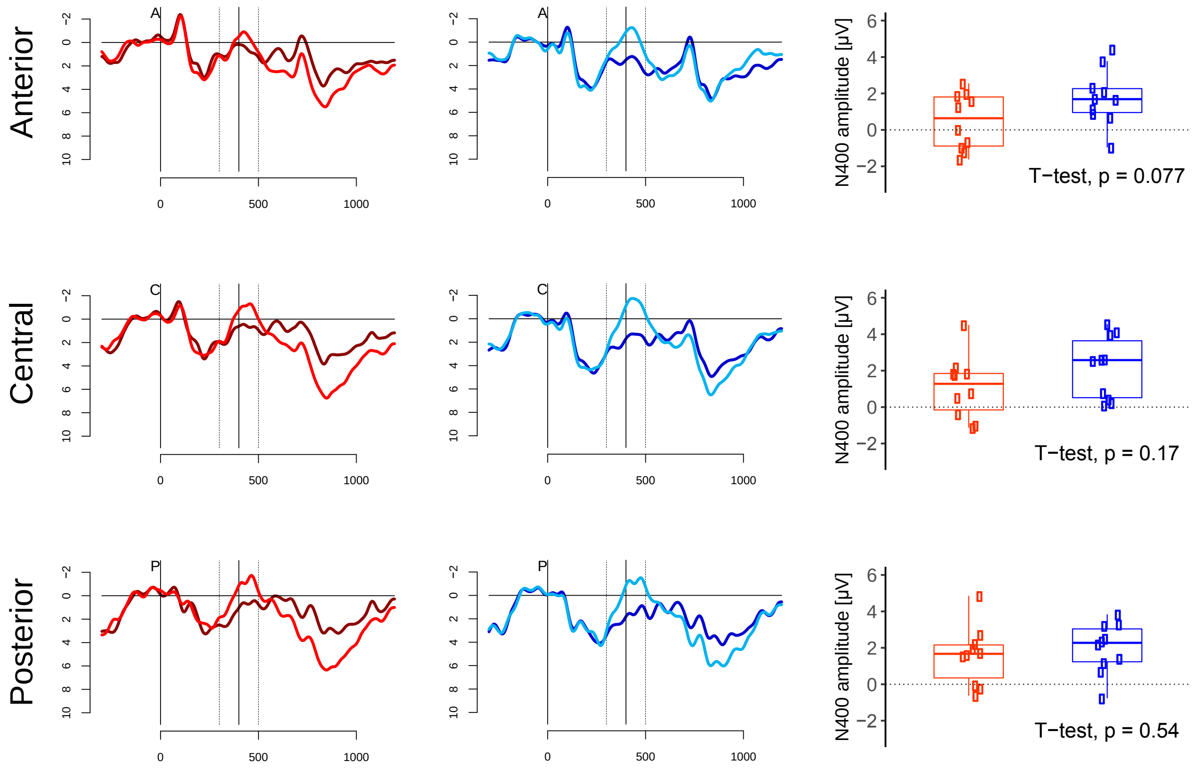

Figure 6.8 B – *Averaged waveforms of the N400 (time window between 300 and 500 ms) responses (left) after stimulus onset in CI users (in red) and normal heraring controls (in blue) for anterior, central and posterior clusters along the central line. Control sentences are represented by the darker line while sentences that contain a violation are displayed with the lighter line. On the right, t-test comparison between CI users (in red) and controls (in blue) for the N400 amplitude (violated condition minus correct condition) expressed with positive values.*

We tested whether there was a correlation between the amplitude of the effect of the N400 and the duration of the time spent with the CI after implantation. Interestingly, this correlation emerged to be statistically significant ($p = 0.03$) suggesting an influence of the CI in the shift toward a stronger semantic strategy (see Figure 6.9). We can speculate that this effect could be due to the difficulties in the auditory perception of fine syntactic elements of the sentence. Although results on the P600 as well as syntactic behavioral measures suggest that they maintain the already acquired syntactic knowledge, the deterioration of the auditory information provided by the CI could induce postlingually deaf CI users to strongly rely on lexical/semantic features during sentence processing. Though, it is still unclear why the N400 effect increases overtime almost suggesting a growing shift toward a semantic strategy regardless of the increasing experience with the CI. Well aware that correlations, especially with a relatively small number of subjects, should be taken carefully, we think that this should be object of future investigations. As expected, we report no correlation between the amplitude of the N400 and the use of the cochlear implant ($p = 0.93$).

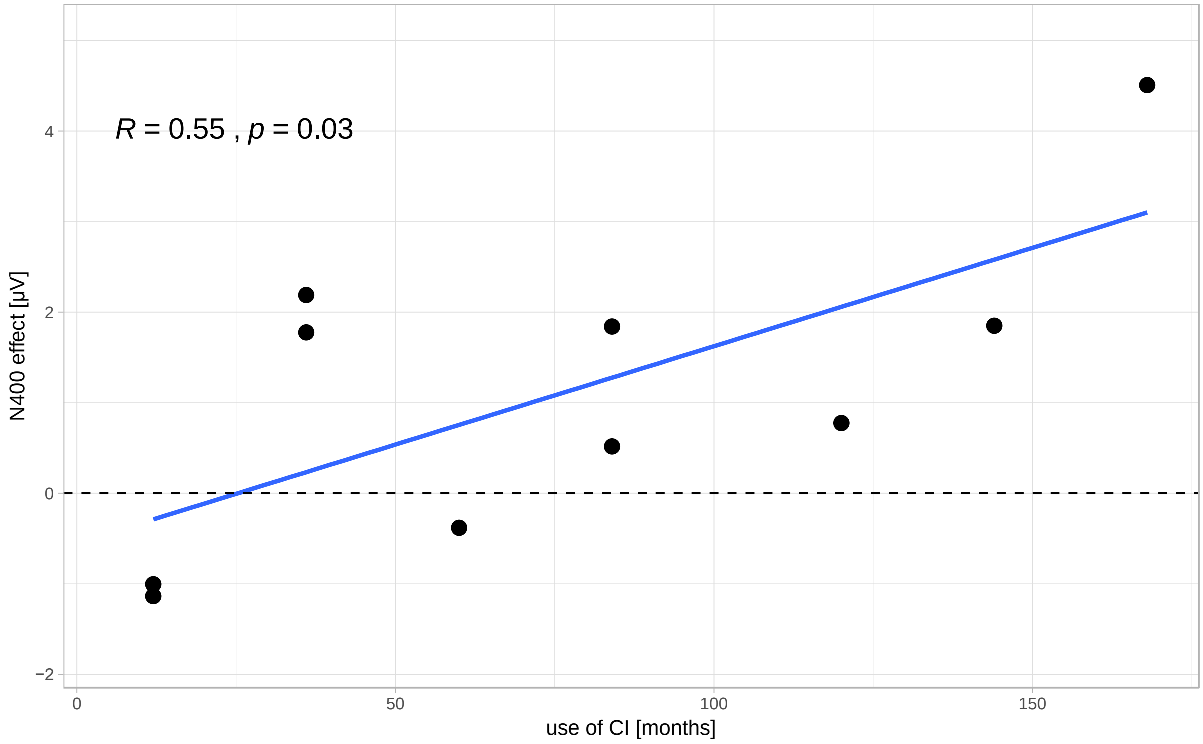

Figure 6.9 – *Correlation between the time expressed in months of the experience with the use of the CI (x axis) and the amplitude of the effect of the N400 (y axis) expressed in microVolt (µV).*

Similarly with what we did for the previous study, we also tried several Kendall's Ranking Correlations (see Figure 6.10), where we correlated the age at 1st implant, the time of CI usage and the age of every single implanted participant with each behavioral test that we conducted including the end-of-sentence acceptability judgement task during the EEG experiment (expressed as a d' index). In addition, for the postlingually deaf CI user's population, we also considered parameters such as the duration of deafness experience. Given the vulnerability of these correlations to be affected by concurrent variables such as age and education, we ran Partial Kendal's Ranking Correlations to double check the validity of the aforementioned correlations. Moreover, we also tried to exploratively correlate the same behavioral tasks with both the N400 and the P600 effects expressed as the difference between the violated and the correct condition in a time window that is the same used in the ERP results. Differently with the Differently from the results found in the study on prelingually deaf CI users, we did not find any statistically significant correlation between N400 and P600 effects and behavioral measures. Also, in this group, the age at first CI does not have a relevant impact as we found in the previous study given the fact that, with the exception of one participant, all of the other subjects of this sample are adults who already acquired language before implantation. Interestingly, the semantic component in this group seems to be more impacted if compared to syntax in the same sample or if compared to prelingually deaf implanted who showed more correlations involving the syntactic components both in the P600 effects and in behavioral measures. This could be easily explained by the fact that postlingually deaf implanted people already acquired the grammar of their first language whereas the vocabulary and the perception of the semantic features can be highly impacted by the use of the CI and by the age at the onset of deafness.

6.3.2.3 – Single subject reliability

We run the same single subject analyses that we have seen in the previous study (see Paragraph 5.3.5). The aim of these analyses is to better understand how the group-level effects that we found for the N400 and the P600 can be generalized to each participant.

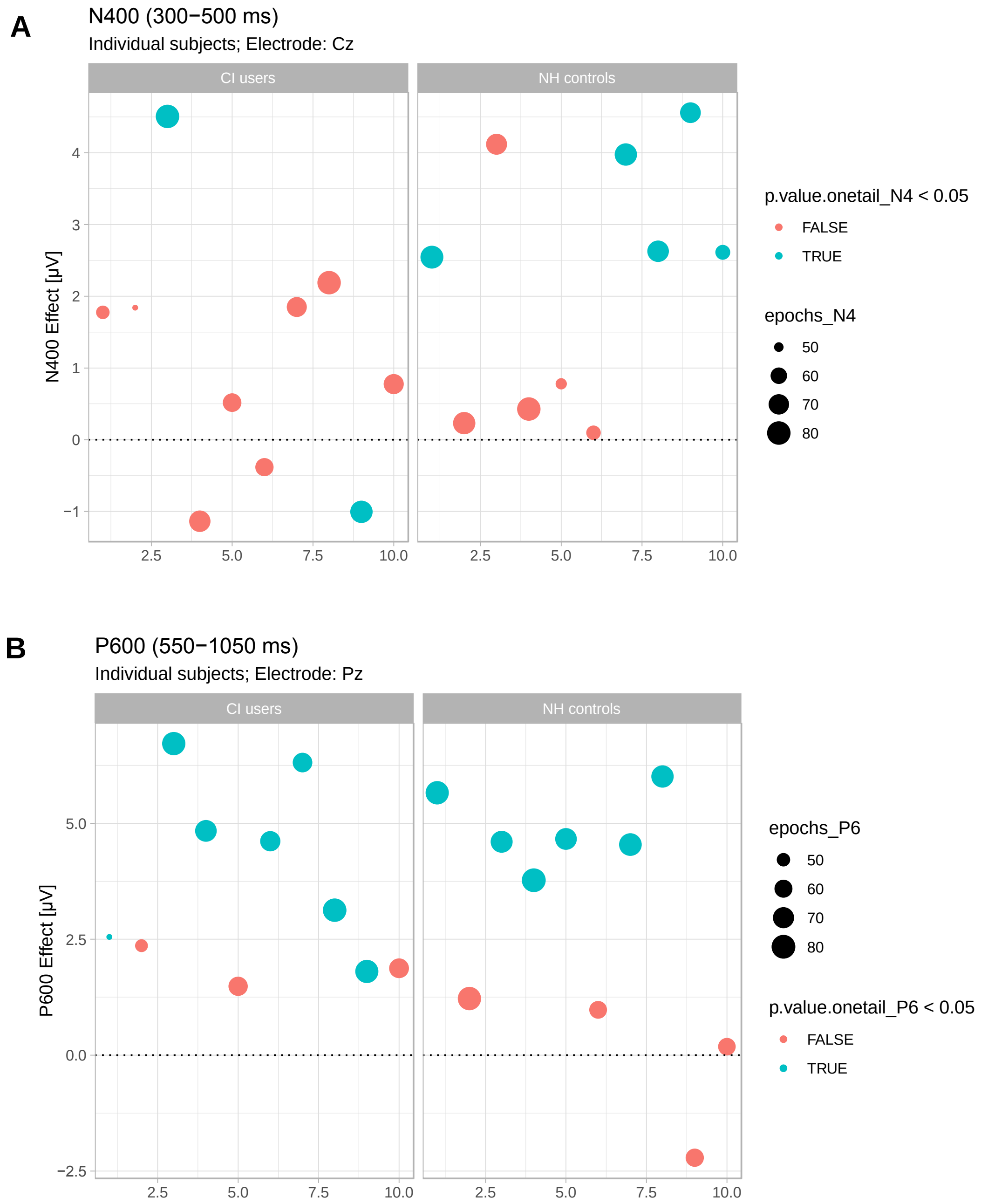

Figure 6.10 – *The plot represents the statistical significance of each participant's N400 (**A**)/P600 (**B**) effect. The two colors represent the one tail p-value where the blue indicates that the p-value is below 0.05 and red for p-values above 0.05. The size of the points represents the number of epochs that are considered in this analysis.*

In the N400 analysis we can see that only two CI users showed single subject statistical reliability; five NH controls showed this statistical significance. More encouraging is the single subject analysis of the P600 where both CI users and NH controls showed a strong effect and reliability also at individual level (see Figure 6.10

B). This result gives us the flexibility to analyze these subjects in smaller groups if necessary, but more importantly, it confirms that the P600 effect that we found at group level is shared by the majority of the participants both in CI users and controls.

6.3.2.4 – Further analyses (LPC; Cloze Probability)

Given the lack in the literature on the comparison between these two groups with the specific aim to test linguistic ERPs in response to violations, we also ran analyses in two possible late positive component (LPC) time windows (500-900 ms/700-1000 ms) and we also tested the Cloze Probability effect as we did in the study on prelingually deaf implanted participants. Again, we run a repeated-measures ANOVA with the same structure of the ones previously employed in order to investigate the late-positive component (LPC) following the N400 and the only significance that we were able to reveal is the main effect of correctness ($F(1, 18) = 12.32$, $p = .003$, $\eta_p^2 = .41$) with again, no significant interaction when group was a factor. We also tried to change the time window of the component based on visual inspection and results were the same. However, visual inspection of the waveforms could suggest that the LPC is actually slightly stronger in the group of CI users especially in the anterior and central clusters (see Figure 6.8). The lack of significance could be caused by the relatively small number of subjects.

Cloze probability also did not statistically show any difference in the comparison between groups although, qualitatively the difference between the correct and the violated condition in the low cloze-probability set of sentences seems to be different between CI users and controls with the first group showing a weaker effect of correctness. This qualitative observation did not result from statistical analyses that might have suffered from the combination of the relatively small sample of subjects and items given that in the cloze probability analyses, the number of the items have to be divided in half. Following analyses from study one, we wanted to separately analyze high cloze-probability and low cloze-probability with correctness collapsed in the difference between the violated and the correct condition specifically looking for differences between groups. However, we still did not find any statistical significance. The ANOVA for high cloze-probability only did not reveal a main effect of GROUP $F(1, 18) = 0.65$, $p = .429$, $\eta_p^2 = .04$ as well as no effect of GROUP was found for the low cloze-probability only analysis $F(1, 18) = 3.22$, $p = .090$, $\eta_p^2 = .15$.

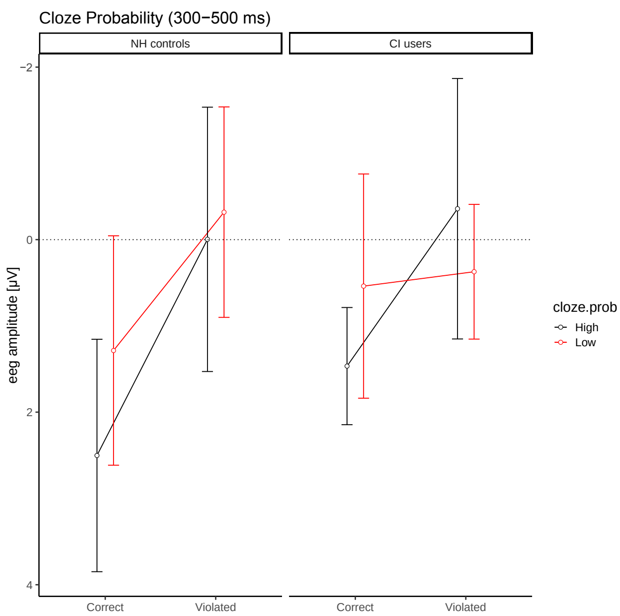

Figure 6.11 - *EEG amplitude in micro Volt (μV) for correct and violated sentences on the x-axis divided for normal hearing control (on the left) and CI users (on the right). The black line represents the high cloze-probability condition and the red line represents the low cloze-probability. Cloze probability was run only among the semantic set of sentences and was analyzed in the time window between 300 and 500 msec after stimulus onset. This plot represents an average of the central luster along the central line (Cz + the 8 electrodes around it).*

6.4 – Discussion

There is a large group of CI users that has been less investigated with the ERP approach in the literature if compared to prelingually deaf CI users for linguistic outcomes after cochlear implantation. However, a large portion of the adult population around the world developed or is at risk of developing a hearing impairment. Among them, some can also develop or suddenly acquire a profound sensorineural deafness which can be treated with cochlear implantation. The group of postverbally deaf CI participants is of great interest because it can provide useful information on the modifications at neural level that can happen when the acoustic route is restored after an acoustic deprivation/degradation experience that occurred late in life. This group of people has a consolidated L1 or at the very least, it started to acquire language for the entire duration of the critical period for language acquisition. The key question we addressed in this study was to what extent partially recovered auditory input through the CI can impact on consolidated language abilities in late deaf CI users. Once again, because all sentence stimuli were presented in our paradigm through the intact visual system, we disentangled difficulties in processing the auditory input from difficulties that could pertain specifically to amodal language processing.

6.4.1 – The P600 and the syntactic processing

When the two groups were tested aiming to test the syntactic processing in postlingually deaf CI users, we didn’t expect to find any difference between them and the control group in the P600 component. However, as mentioned in the introduction, we couldn’t make strong predictions in this direction given the possibility that the impaired auditory information provided by the CI could have modified the neural processes behind reading. With respect to the P600 in its entire time window, the two groups did not show any difference at all. Comparable results were also found in the analysis of the left-anterior negativity (LAN), late positive component (LPC) and cloze probability, with the interactions with the between factor -GROUP- never reaching or approaching the significance threshold. Although the sample is relatively small, with 10 participants per group, both the N400 and the P600 effects are also present with single subject statistics especially supporting the homogeneity of the P600.

6.4.2 – The N400 and the semantic processing

With respect to the semantic processing, we had strong predictions where we expected no differences in the comparison between the two groups. However, in light of the results from the previous study, we also were looking for possibly a stronger reliance on semantic features that perhaps, could have resulted in a stronger N400 effect. We tested them in the N400 time window where our results did not show any N400 difference between groups in the grand-averaged EEG signal. However, the correlation between the amplitude of the N400 effect and the time spent with the CI, suggest that our semantic-shift prediction was in fact correct. The growth of the signal with the increase of CI use suggests that the longer the exposure to a degraded acoustic signal the more semantic features could play a major role in written sentence processing. This result is particularly interesting if paired with the stronger N400 effect that we found in the study with the preverbally deaf CI users where the N400 effect resulted to be stronger in the experimental group compared to hearing controls.

6.4.3 – Summary, limitations and future directions

To summarize, we did not find any difference in the neural signatures of language processing between postlingually deaf CI users and age-matched hearing controls while reading written sentences with embedded lexical-semantic and syntactic number-agreement violations. Interestingly, the positive correlation that we found between the duration of CI usage and the amplitude of the N400 effect suggest that there could be a relationship between altered auditory signal on written language processing. No similar correlations were found in the syntactic condition where neither the duration of CI usage nor the age at implantation, correlated with the amplitude of the P600 effect.

These results added useful information about the impact that cochlear implantation might have on linguistic correlates during a reading task. Despite being comparable to age-related hearing controls, for ERP responses and behavioral measures, postverbally deaf CI users showed an interesting trend toward a semantic strategy that should be further investigated. Furthermore, future studies should probably increase the number of participants to increase the power of the correlations. It is also important to mention that results from this study, should be taken as a sign of the efficacy of CIs by acknowledging that our CI users' sample was a selection among people that faced a good outcome after CI activation. Thus, this sample is not necessarily representative of the entire population of postverbally deaf CI users.

Chapter 7

7.0 – General Discussion

In this thesis, we aimed to investigate how language acquisition and processing can be modulated after cochlear implantation. To this aim, we ran two experiments aiming to better understand how cochlear implant can impact neural processes subtending reading written sentences. We chose a widely employed ERP technique, in which sentences are presented one word at a time, either in their correct form or with embedded semantic or syntactic violations. We focused on well-established ERP components, like the N400 and the P600 for the analysis of semantic and syntactic features respectively. Furthermore, we tested the reliability of our experiment by collecting a large group of hearing controls in a wide age-range (12 to 65 years old). We have exploited this new dataset also, to examine changes in EEG responses to sentence processing as a function of age.

Thanks to the robust paradigm confirmed by single-subject level reliability and thanks to the points of strength of our experiment, we have been able to replicate results in the literature eliciting a clear N400 effect in response to semantic incongruities and a P600 in response to syntactic number-agreement violations in both the experimental and control group. This allowed us to focus the attention on the comparison between each clinical group and its age-matched hearing control sample. Our experiment, even though it has been started before the publication from Mehravari and colleagues in 2017 (Mehravari et al., 2017) has been, since then, compared to this study because of their similarities in the employed paradigm and more importantly for the recruitment of a deaf group. However, several differences exist between the two studies. First, our participants were implanted while their clinical group was not;

second, our experiment was in Italian while the other experiment has been conducted in English; finally, we employed double the number of the stimuli for each condition. Our results differed from Mehravari for the analysis of the semantic processing where we found a stronger N400 effect in the preverbally deafness group of CI users whereas they found a comparable N400 effect across populations. Critically, we also found a comparable P600 effect in both the CI users and in the hearing control group, likely suggesting that the CI seems to be capable to restore typical neural signatures of language acquisition and processing. Overall, despite showing a small disadvantage in some behavioral scores, we found preverbally deaf CI users to have a very good level of language development which is a result that should be attributed to the cochlear implant as well as the surrounding environment that is important to support cochlear implantation both psychologically and in the everyday practice. Moreover, the correlations that we found between the P600 and the age at first implantation in our preverbal group proved the importance of early implantation in respect of the restoration of the typical networks for language processing. In the prelingual group, the decrease of the amplitude of the P600 effect correlated to the increase of the age at implantation. We believe our work extend the implications of the work by Mehravari et al. (2017). They did not find any P600 effect in deaf individuals who did never received a cochlear implant. Thus, we can ideally imagine the deaf group of Mehravari to be at the very end of our correlation with no P600 effect associated to a “null” age at implantation. Hence, these results support the hypothesis of a critical period for language acquisition, already present in the literature (among the others, Caselli et al., 2012; Ann E. Geers, 2004; Ann E. Geers, Mitchell, Warner-Czyz, Wang, & Eisenberg, 2017; Kral & Sharma, 2012; Niparko et al., 2010; Rinaldi et al., 2013). This is a crucial point of this work since one of our primary aims was to understand whether the age at implantation could have impacted ERP correlates of written language processing by using complex linguistic stimuli. As suggested from one of the reviewers of this manuscript, data from the study from Skotara (2011) and from Mehravari (2017) reported different findings by showing (the first) a P600 effect in response to syntactic violations while the second by not showing any syntactic effect in response to violation. Since our results highlighted a similar pattern between CI users and NH controls, we could argue that it is not deafness per-se to cause a modulation of the components. In fact, by being implanted or by developing language through signs, seems to be enough to show comparable ERP components when compared with age matched hearing controls. From a purely linguistic point of view, this enforced even more the importance of the development of a first language regardless of the modality and/or the choice of whether or not to implant.

Our second study (Chapter 6) suggested that CI does allow late deafness implanted users to proficiently maintain the level of language experience that this group had before. Behavioral measures did not capture any relevant differences between the experimental and the control group and the ERPs were statistically comparable with both an N400 and a P600 elicited by their respective violations. However, the correlation between the N400 effect and the time of CI use (years of active CI usage after activation) suggests that there may be some modifications in the strategies employed by late deaf CI users when reading written sentences, following extended exposure to altered auditory language due to CI use. This is especially interesting in light of the stronger N400 effect found in early deaf CI participants who also seemed to show a semantic strategy shift.

The third study (Chapter 4) investigated the ERPs that were used in the first two experiments, by trying to understand how these EEG components change over the course of life. We had a large sample of normal developed control participants and we divided them in 4 groups of age with 12 participants in each subsample. Visual inspection provided us many interesting information with the P600 being more frontally distributed in older adults compared to younger adults and young individuals which could suggest that different networks are activated when processing syntactic features across the lifespan. Further visual inspection revealed the presence of a LAN-compatible topography in the second group (from 19 to 28 y.o.). This negativity preceding the P600 is however differently distributed in groups three and four, it can be described as a Left Temporal Negativity given the shift toward central-posterior sites. In the first group of young individuals, this negativity can be confused with an N400 after the superposition of negative and positive responders. However, given the small number of subjects, it would be unlikely to see such a strong N400 and P600 in the case of an effect of a grand-average artifact. The N400 across ages resulted to be stable with the effect being present with a typical central distribution on the scalp for all tested groups.

These results are of great encouragement for clinicians and cochlear implant surgeons, but they do highlight that CI is still a tool that must be further studied and that must be accompanied by a thorough speech therapy path and social care. Our studies with CI users have a rather uncommon within-group homogeneity (apart from the age at implant) and while this is very good for statistical analyses and results reliability, we did not include bad-outcome implanted people. Hence, our sample is representative of the efficacy of good-outcome CI individuals which is an important factor to be considered when use and share these results.

Future studies that will employ similar paradigm to the one used in this project, should increase the number of the items per condition given that we proved the importance of having a large number of stimuli. However, the RSVP paradigm should also be followed by similar EEG experiments that use more naturalistic stimuli such as texts presented entirely, possibly tracking eye movements while recording ERPs. Moreover, the range of violations should be increased although it represents a challenge for the nature of the EEG technique itself. The study of linguistic ERPs and even more, their applications in such a complex clinical population like the deaf implanted groups that we tested represents an interestingly challenge for future studies and we think that we were able to add a relevant brick in the wall.

Supplementary material

N=13		Kendall's correlation			Partial correlations	
		Age at 1st CI	CI use	Age	A. 1st CI - Age	CI use - Age
Behavioral tasks	SPM	p-value = 0.6299, tau= -0.12	**p-value = 0.02654**, tau=0.53	**p-value = 0.02453**, tau= 0.55		NA
	SFT	p-value = 0.6212, tau= -0.11	p-value = 0.5822, tau= 0.12	p-value = 0.2937, tau= 0.23		
	GAT	p-value = 0.07775, tau= -0.46	p-value = 0.6485, tau= 0.12	p-value = 0.579, tau= 0.15		
	LexDec RT	p-value = 0.09593, tau= 0.36	p-value = 0.6754, tau= -0.10	p-value = 0.8532, tau= -0.04		
	LexDec Acc	p-value = 0.6193, tau= -0.11	**p-value = 0.009833**, tau= 0.55	**p-value = 0.003512**, tau= 0.64		p-value = 0.72
	EDT	p-value = 0.9499, tau= -0.01	p-value = 0.3192, tau= 0.22	p-value = 0.1665, tau= 0.31		
	d'sem	**p-value = 0.03091**, tau= -0.46	**p-value = 0.03048**, tau= 0.46	p-value = 0.07374, tau= 0.38	p-value = 0.034	p-value = 0.209
	d'synt	**p-value = 0.04186**, tau= -0.44	p-value = 0.2044, tau= 0.28	p-value = 0.355, tau= 0.20	p-value = 0.051	
EEG	N400_est	p-value = 0.7578, tau= 0.07	p-value = 0.9524, tau= -0.03	p-value = 0.9508, tau= -0.01		
	P600_est	**p-value = 0.04186**, tau= -0.44	p-value = 0.2519, tau= 0.26	p-value = 0.355, tau= 0.20	p-value = 0.051	

	Kendall's correlation	
	N400_effect	P600 effect
SPM		p-value = 0.3418, tau= 0.23
SFT	**p-value = 0.01714**, tau= 0.50	
GAT		**p-value = 0.03602**, tau= 0.54
LexDec RT	p-value = 1, tau= 0	
LexDec Acc	p-value = 0.9022, tau= 0.03	
EDT		p-value = 0.455, tau= 0.16
d'sem	p-value = 0.1635, tau= -0.31	
d'synt		**p-value = 0.0000703**, tau= 0.77

	N=12	Kendall's correlation			Kendall's Partial correlations	
		Age at 1st CI	**CI use**	**Age**	**Age 1st CI - Age**	**CI use - Age**
Behavioral tasks	**SPM**	p-value = 0.7806, tau= 0.07	p-value = 0.08326, tau= 0.44	p-value = 0.03274, tau= 0.56		NA
	SFT	p-value = 0.3294, tau= -0.22	p-value = 0.3025, tau= 0.23	p-value = 0.2961, tau= 0.24		
	GAT	p-value = 0.1246, tau= -0.44	p-value = 1, tau= 0	p-value = 0.9131, tau= 0.03		
	LexDec RT	p-value = 0.06057, tau= 0.43	p-value = 0.6384, tau= -0.12	p-value = 0.8348, tau= -0.05		
	LexDec Acc	p-value = 0.7264, tau= -0.08	p-value = 0.007073, tau= 0.60	p-value = 0.01177, tau= 0.58		p-value = 0.3196021
	EDT	p-value = 0.4814, tau= -0.16	p-value = 0.08228, tau= 0.39	p-value = 0.1054, tau= 0.38		
	d'sem	p-value = 0.04384, tau= -0.46	p-value = 0.04474, tau= 0.46	p-value = 0.1099, tau= 0.36	p-value = 0.0407303	p-value = 0.1776186
	d'synt	p-value = 0.03119, tau= -0.49	p-value = 0.1969, tau= 0.30	p-value = 0.3662, tau= 0.21	p-value = 0.0349438	
EEG	**N400_est**	p-value = 0.9446, tau= -0.02	p-value = 0.8406, tau= 0.06	p-value = 0.9446, tau= 0.02		
	P600_est	p-value = 0.04384, tau= -0.46	p-value = 0.3108, tau= 0.24	p-value = 0.4445, tau= 0.17	p-value = 0.04960074	

	Kendall's correlation	
	N400_effect	**P600 effect**
SPM		p-value = 0.5234, tau= 0.16
SFT	p-value = 0.03311, tau= 0.47	
GAT		p-value = 0.03234, tau= 0.59
LexDec RT	p-value = 0.9466, tau= -0.03	
LexDec Acc	p-value = 0.7299, tau= 0.08	
EDT		p-value = 0.2971, tau= 0.24
d'sem	p-value = 0.3108, tau= -0.24	
d'synt		p-value = 0.00004, tau= 0.82

N=10		Kendall's correlation					
		Age at 1st CI	**CI use**	**Deafness onset**	**Deafness duration**	**Education**	**Age**
Behavioral tasks	**SPM**	p = 0.02371, tau= -0.67	p = 0.8993, tau= 0.04	p = 0.4509, tau= -0.22	p = 0.022, tau= -0.71	p = 0.3683, tau= 0.28	p = 0.04438, tau= -0.59
	SFT	p = 0.4843, tau= -0.2	p = 0.4689, tau= 0.18	p = 0.1557, tau= -0.38	p = 0.9261, tau= 0.02	p = 0.6458, tau= 0.12	p = 0.7275, tau= -0.11
	GAT	p = 0.5234, tau= -0.16	p = 0.3565, tau= -0.24	p = 0.9274, tau= -0.02	p = 0.2991, tau= -0.28	p = 0.7789, tau= 0.08	p = 0.316, tau= -0.26
	LexDec RT	p = 0.8016, tau= 0.07	p = 0.3756, tau= 0.26	p = 0.4509, tau= -0.22	p = 0.2811, tau= 0.33	p = 0.1575, tau= -0.43	p = 1, tau= 0
	LexDec Acc	p = 0.4411, tau= 0.23	p = 0.5179, tau= 0.20	p = 1, tau= 0	p = 0.4094, tau= 0.26	p = 0.793, tau= 0.08	p = 0.3044, tau= 0.31
	EDT	p = 0.09964, tau= -0.49	p = 0.6098, tau= -0.15	p = 0.2543, tau= -0.34	p = 0.4155, tau= -0.26	p = 0.01389, tau= 0.76	p = 0.09964, tau= -0.49
	d'sem	p = 0.8618, tau= 0.07	p = 0.4689, tau= -0.18	p = 0.02861, tau= -0.56	p = 0.1643, tau= 0.36	p = 0.2321, tau= 0.31	p = 0.8618, tau= 0.07
	d'synt	p = 1, tau= -0.02	p = 0.4689, tau= -0.18	p = 0.2912, tau= -0.23	p = 0.643, tau= 0.12	p = 0.3119, tau= 0.26	p = 0.7275, tau= -0.11
EEG	**N400_est**	p = 1, tau = 0.02	p = 0.02979, tau= 0.55	p = 0.01667, tau= -0.6	p = 0.3078, tau= 0.26	p = 0.6458, tau= -0.12	p = 1, tau= 0.02
	P600_est	p = 0.1557, tau= -0.38	p = 0.4689, tau= -0.18	p = 0.002213, tau= -0.73	p = 0.9261, tau= 0.02	p = 0.5199, tau= 0.17	p = 0.1557, tau= -0.38

	Kendall's correlation	
	N400_effect	**P600 effect**
SPM		p = 0.1316, tau= 0.45
SFT	p = 0.2164, tau= 0.33	
GAT		p = 0.9274, tau= -0.02
LexDec RT	p = 0.4509, tau= 0.22	
LexDec Acc	p = 0.1234, tau= 0.46	
EDT		p = 0.3753, tau= 0.27
d'sem	p = 0.3807, tau= 0.24	
d'synt		p = 1, tau= 0.02

Kendall's Partial correlations									
Age 1st CI - Age	**CI_use - Age**	**Deaf onset - Age**	**Deaf duration-Age**	**Edu - Age**	**Age 1st CI - Edu**	**CI_use - Edu**	**Deaf onset - Edu**	**Deaf duration - Edu**	**Age - Edu**
NA			NA		NA			NA	
				NA					
		p = 0.02391217					p = 0.03476292		
	p = 0.02658883	p = 0.0174066				p = 0.03369814	p = 0.02108828		
		p = 0.008218294					p = 0.005902395		

In order from the first to the latter: tables with Kendall's ranking correlational analyses and Kendall's ranking partial correlations. The first table refers to prelingually deaf CI users (chapter 5) with all of the participants included (N=13). The second table instead, doesn't include one participant because, as explained in the dedicated paragraph, represented an outlier because of its age at first implant. The third table contains the analyses for postlingually deaf CI users.

All three tables contain ranking correlations between behavioral measures and individual variables (top); behavioral measures and ERPs (bottom in 1 & 2; right in the third) and partial ranking correlations (right in 1 & 2; bottom in the third). Correlations between behavioral tasks and ERPs have been made only between coherent couples (e.g. semantic tasks with the N400; syntactic tasks with the P600).

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